A Study on Fault Tolerant Wide-Area Controller Design to Damp Inter-area Oscillations in Power Systems

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A Study on Fault Tolerant Wide-Area Controller Design to Damp Inter-area Oscillations in Power Systems

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Supervisor's Certificate

This is to certify that the work presented in the dissertation entitled **A Study on Fault Tolerant Wide-Area Controller Design to Damp Inter-area Oscillations in Power Systems** submitted by *Anubhav Sundaria*, Roll Number *214EE3236*, is a record of original research carried out by him under my supervision and guidance in partial fulfillment of the requirements of the degree of Master of Technology in Electrical Engineering. Neither this dissertation nor any part of it has been submitted earlier for any degree or diploma to any institute or university in India or abroad.

Prof. Sandip Ghosh

Dedication

To My Parents, Family and Friends

Anubhav Sundaria

DECLARATION

I, *Anubhav Sundaria*, Roll Number *214EE3236* hereby declare that this dissertation entitled *A Study on Fault Tolerant Wide-Area Controller Design to Damp Inter-area Oscillations in Power Systems* presents my original work carried out as a postgraduate student of NIT Rourkela and, to the best of my knowledge, contains no material previously published or written by another person, nor any material presented by me for the award of any degree or diploma of NIT Rourkela or any other institution. Any contribution made to this research by others, with whom I have worked at NIT Rourkela or elsewhere, is explicitly acknowledged in the dissertation. Works of other authors cited in this dissertation have been duly acknowledged under the sections Reference or Bibliography. I have also submitted my original research records to the scrutiny committee for evaluation of my dissertation.

I am fully aware that in case of any non-compliance detected in future, the Senate of NIT Rourkela may withdraw the degree awarded to me on the basis of the present dissertation.

May 25, 2016
NIT Rourkela

Anubhav Sundaria

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Abstract

Due to increased power supply demand, power system oscillations has become a major concern to have stable and secure system operation. One of the major concern in a power system is to damp inter-area oscillations. Lack of proper damping may lead to growing nature of low frequency oscillations which may limit power transfer capability and sometimes even blackouts. Power system stabilizer is used to damp local oscillations but it is not efficient to damp inter-area oscillations due to less observability of wide-area signals. Wide-Area Measurement Systems is used to overcome this issue and damp inter-area modes to an adequate level. Wide-area controller based on PSS takes difference of local and remote speed deviation signals as feedback and feeds the exciter of the selected machine.In order to select feedback signals and controller location, wide-area loop selection method using geometrical measure approach is performed. However, while obtaining local and remote signals, a time-delay is introduced that may degrade the performance of system or may lead to instability. Two configurations are defined depending on feedback i.e. synchronous and non-synchronous feedback. The time-delay is modeled with 2^{nd} order Pade approximation. The time-delay effect in both configurations is then studied. The controller is synthesized based on H_∞ mixed sensitivity method with regional pole placement for a 4 machine 11 bus power system. It can be found that WDC damps out oscillations quickly and improves performance.

Next problem considered is to design a controller for the case study on a 4 machine 11 bus power system when there is a sudden loss of remote signal, i.e. faulty conditions. A conventional control (CC) method is used to design controller considering a local signal always available and a comparison is made in plants performance for normal and faulty conditions. It is found that conventional control method degrades performance in faulty situation and may lead to instability. To address this problem, a passive fault tolerant control (FTC) method is used where an iterative procedure is used for design and found that the system maintains adequate stability even in faulty conditions. Several methods are available to design the controller but LMI approach was found relatively simple and is used here. For FTC method, the control effort required was more compared to CC method. However, FTC controller provides acceptable performance than CC controller.

Key words: ***Power System Stabilizer, Wide-Area Control, Time-delay, Synchronization, Conventional Control, Fault Tolerant Control.***

Contents

List of Symbols and Acronyms

List of Symbols

$\Re$	:	The set real numbers
$\Re^n$	:	The set of real n vectors
$\Re^{m\times n}$	:	The set of real $m \times n$ matrices
$\|\|X\|\|$	:	Euclidean norm of a vector or a matrix X
$\in$	:	Belongs to
$< (\leq)$	:	Less than (Less than equal to)
$> (\geq)$	:	Greater than (Greater than equal to)
$\neq$	:	Not equal to
$\forall$	:	For all
I	:	An identity matrix with appropriate dimension
X^T	:	Transpose of matrix X
X^{-1}	:	Inverse of X
$\lambda(X)$	:	Eigenvalue of X
$X > 0$	:	Positive definite matrix X
$X \geq 0$	:	Positive semidefinite matrix X
$X < 0$	:	Negative definite matrix X
$X \leq 0$	:	Negative semidefinite matrix X

List of Acronyms

LMI	:	Linear Matrix Inequality
PSS	:	Power System Stabilizer
PMU	:	Phasor Measurement Unit
WDC	:	Wide-area Damping Controller
WAMS	:	Wide-Area Measurement System
AVR	:	Automatic Voltage Regulator
LSI	:	Loop Selection Index
MISO	:	Multiple Input Single Output
CC	:	Conventional Control
FTC	:	Fault Tolerant Control

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CHAPTER 1

Introduction

1.1 Overview and Motivation

With the growing population, electric power requirement is increasing day by day. Power system is operated closer to it's limits due to continuous increase in demand for supply. So, one of the goals for power system operator is to boost up the transfer capability of power and maintain a stable system. Stability of power system in such a case is the major issue to deal. The huge transfer of power on long distance weak tie lines create small signal oscillations. Such oscillations leads to instability and blackouts of power system. Generation system operates close to their limit due to deregulation of power system. So it leads to stressed condition of system and inherent low damping of the system may not be sufficient to retain the system stability. Oscillation occurs in power system due to the existence of the various dynamical components after a disturbance. These oscillations may grow and lead to the loss of synchronism in the absence of proper control.

Different forms of power system instability have emerged due to continuous expansion in interconnection. Stability issue depending upon the physical parameters is classified into three categories a) Rotor angle stability b) Voltage stability and c) Frequency stability. Stability study also depends upon the magnitude of disturbances and is divided into two types Small Signal Stability and Transient Stability. When power system is subjected to small disturbances, the ability of the system to maintain synchronism is called Small Signal Stability [13]. The lack of sufficient synchronizing torque and so generator rotor angle increases or rotor oscillations amplitude increase leading to such instability. The ability of power system to return to normal operating state even after severe transient disturbance is called Transient Stability [13]. The paper is to tackle small signal stability issue and so it is our point of interest. Power system oscillation occurs with different modes like swing modes, torsional modes, exciter modes etc. Swing modes are of two types a) Local Mode b) Inter-area Mode. When a generator oscillates against generators belonging to the same area then the oscillations is considered as local mode. For local mode, frequency range from 1 to 3 Hz. When a generator oscillates against generators belonging to different area then the oscillations is considered as inter-area mode. It's frequency range from 0.1 to 0.9 Hz. Inter-area modes occur due to either heavy power transfer across weak tie-lines of high gain exciters. An AVR provides synchronizing torque component but lacks damping torque component [13], resulting in oscillations in power system.

To damp these oscillations, a damping controller called Power System Stabilizer (PSS) is used. It provides damping torque component through exciter. But PSS considers only local dynamics i.e. takes feedback from local generator only. PSS considers feedback of local signal only and has less observability of inter-area oscillations. In order to deal with inter-area oscillations, Wide Area Controller (WAC) is designed which takes remote signals as feedback and fulfils the demand of lacking observability for remote signals. Phasor Measurement Unit (PMU) gives better dynamic data which is computer based technique, used to estimate phasors in real time for monitoring and control [18]. Remote signals are thus can be available for designing a controller (WAC) for better performance. To achieve same amount of performance, a local controller requires much gain compared to wide-area controller. A WAC is 4 to 20 times efficient than the local controller.

WAMS provides better dynamic data of the system but involvement of remote signals arise time-delay of latency due to signal transmitting from PMUs to PDC, and then back to generators. Transmission delay is due to various factor such as protocol, traffic and communical link. Computational delays add extra delay occur due to processing signals and synchronization. In the Western Electricity Coordinating Council(WECC), a delay of 25 ms was reported for fibre optic cable whereas 250 ms was the delay for satellite communication link delays. For Nordic power system in [6], a delay of 150 ms was reported and 100 ms of delay in Chinese power system in [25]. In some other report, Indian WAMS reported a delay of 250 ms. An infinite numbed of poles are introduced in the system with right hand zeros due to time delay. Introduction of time delay may lead to instability or may lose synchronism in power system. Communication and operational delays, both plays an important role on system performances. Communication delay range from few millisecond to orders of hundred milliseconds [16]. Operational delay is synchronization of signals in which receiving and resolving PMU data and data synchronization with respect to GPS time-stamp occurs.

The feedback signal measurements from PMUs are sent to PDC and then to WAC. Two types of configuration exist depending upon feedback signal to the controller i) Synchronous ii) Non-Synchronous. Inter-area mode can be seen as difference signal from two areas, so it is best suitable to be feedback to the controller. In synchronized feedback, local and remote signals have and equal amount of time delays and are then fed to the controller. In non-synchronized feedback, delay in local signal is negligible with consideration of delay in remote signal.

A situation comes when fault occurs in feedback of remote signal. In a Conventional Control (CC) method, performance degrades whenever there is a sudden loss of a remote signal. Following a sudden loss of remote signal, the challenge is to maintain a minimum level of dynamic performance with only the local signal. To address this problem, a fault tolerant control (FTC) design is used. This methodology is based on pole-placement for normal and loss of remote signals along with minimization of control effort. FTC requires more control effort as compared to CC under normal condition . The performance of CC is unacceptable in case of loss of the remote signals but FTC is able to produce an acceptable performance in such case.

1.2 Literature Review

Inter-area oscillations have been a problem leading to even blackouts. A study on Inter-area oscillations is presented in [11].To solve the problem of oscillations in power system using WAMS technology, several methods had been adopted. An introduction to WAC system in power systems is presented in [3]. The wide-area controller was designed based on phase compensation in [2] which was the beginning of wide-area system design. In a report, lead-lag compensator had been used with two loops PSS and a WAC provides extra damping to local oscillations. Lead-Lag compensator design is easy to design but lacks an important issue of robustness and performs non-uniformly with varying operating conditions. Adaptive control method of approach plays a very good role in WAC design and also solve varying operating conditions. A data-driven adaptive controls depends on large disturbances in order to train parameters of a controller and this training may encounter convergence problems.

Predictor based approach has been used in a paper, where a paper use smith predictor to tackle damping issue while the other paper use generalized predictive control with RLS base model identification to make the system adaptive in nature.

An LQG controllers as a WAC is based on minimization of cost function which penalize state deviation and minimize control effort. H_∞ control method in control theory has been superior to any other control method to achieve robustness[24]. H_∞ loop shaping approach with regional pole placement in [14], where normalized LMI approach is used to achieve multiple objectives. In [26, 5], H_2/H_∞ mixed sensitivity design with regional pole placement is proposed. In H_∞ mixed sensitivity method with regional pole placement, controller is designed with appropriate weight matrices in order to minimize control effort and reduce disturbance and noise.

Many wide-area signals are available in power system. To damp inter-area oscillation, the signal mainly corresponding to inter-area mode is to be selected as this will reduce PMU installations costs [10].

The effect of delays in all the above mentioned methods had not been considered which is introduced during fetching of information. Delay effect has been studied in [17, 15]. In H_∞ control framework, uncertainty in delay is handled in [9] by linear transform model.

A sudden fault of sensor or actuator or both i.e. the problem of unacceptable delays or loss of one or more remote signals could degrade system performance. Generally repair and maintenance service can't be provided immediately. So to address this issue, the fault tolerant control (FTC) design theory is an important area of research[21, 22]. The objective behind this theory is to minimize the degradation when a fault occurs in the system. Oscillation damping in a Nordic equivalent system is presented in [4] and a introductory theory on FTC is presented in [23]. In FTC theory, many approaches have been done such as: Coprime factorization approach, Hamilton Jacobi based approach, Riccati equation based approach, Sliding Mode control approach, and the Linear Matrix Inequality (LMI) approach. Among all, the LMI approach [7] is one of the popular in the field as its simpler to implement. Two different approaches exist in FTC theory: active and passive FTCs. In active FTC, whenever a fault occurs the controller is reconfigured. In passive FTC (FTC_p), the controller is fixed for both normal and fault condition. FTC_p is obtained by a priori design based on fault models, so that the controller is able to tackle all the possible faults. In this paper, as the power industry use passive control structures, so we concentrate on this particular scheme.

Due to PMUs, power system dynamics monitoring and analysis have been significantly improved. Although PMUs are not likely to fail but a failure could affect severely, which leads to research of FTC area. Conventional Control schemes (CC) may not work in critical case. FTC scheme maintain stability and increase reliability even if one or more remote signal is lost. Algorithm to design robust controller which can damp oscillations and also the change of variables which is required is presented in [19]. In this work, a case study on two area, four machine and eleven bus power system is presented. Using of local signals doesnt achieve good damping ratio, so it justifies the use of remote signals. Using Conventional Control in which a local and a remote signal is shown to achieve desired performance under normal condition (i.e., remote signal exists). However when loss of remote signal occurs, the response of system deteriorates in open loop response which is unacceptable. A passive FTC method is thus proposed to ensure an acceptable performance level even after loss of remote signals. This methodology is based on simultaneous pole placement of multiple operating conditions that is normal and loss of remote signals and an algorithm to design controller is described.

1.3 Objective

The primary goal is to improve dynamics of power system in both normal and faulty conditions, and for that a controller is to be synthesized.

- A model is to be developed for the complex power system in MATLAB to acquire the dynamics of it. Then an analysis is performed for characterization of the system.
- The model obtained can be of large order which leads to large time in computation of the required controller. So the model order is reduced so that it retains input-output behavior at desired frequency range.
- As PMUs are costly, one need to minimize number of signal needed for the operation.
- A suitable controller is designed to damp inter-area modes and also it should handle the uncertainty in operating conditions in power system.
- While fetching wide-area signals, time delay occurs and that may degrade system performance. So appropriate approach to handle delays is to be taken.
- Sudden fault may occur in sensors or feedback signals leading to deterioration of system performance. Repair services cannot be provided immediately. So, controller is to be synthesized to handle faulty (loss of remote signal) and normal conditions both simultaneously.

1.4 Organization of the Thesis

Chapter-1) Introduction to the problem and also discussion of the earlier works have been done here.

Chapter-2) Power system modeling is illustrated in this chapter. Modal analysis is then presented. Loop selection is discussed to minimize the signal requirement. Finally it talks about model order reduction due to large order of power system model.

Chapter-3) It gives a theory to design WAC controller. The chapter starts with the formalization of synchronous and non-synchronous delay configuration. Then discussion of H_∞ mixed sensitivity formulation with regional pole placement via LMI is done.

Chapter-4) It gives a control theory on how to tackle faulty situation i.e. when sensors or feedback signals are lost and design a suitable controller theory to tackle the situation. CC and FTC schemes are studied.

Chapter-5) Here, a case study is taken to illustrate the objectives, on 4 machine 11 bus system to design WAC. Results have been shown in step wise manner and appropriate discussions were made. How non-synchronous feedback is much better than synchronous feedback is discussed. Then a case study on 4 machine 11 bus system is done in fault condition. A study on CC and FTC is done and the results are compared and found that system requires model of FTC in fault conditions.

Chapter-6) Conclusion of the whole thesis and further future work are discussed here.

CHAPTER 2

Modeling of Power System for Stability Studies

2.1 Small Signal Modeling of Power System

Power system is complex and non-linear in nature. Stability analysis of such a system is highly cumbersome. So to develop a model to capture all the dynamics of it is almost impossible so a mathematical model that can capture particular dynamics correctly needs to be developed. Due to power systems complexity, subsystems of the whole system is considered and then a relation between those subsystem is done via algebraic equations.

2.1.1 Excitation System

Excitation system is used to setup essential flux through DC field current in a generator. It provides control over reactive power flow, voltage and improves system stability. Figure(2.1) below represents block diagram for excitation system . It can be AC, DC or static.
a) Automatic Voltage Regulator (AVR): AVR is used to amplify control signal to the desired level and then convert it in the form for the control of the exciter. So, it controls voltage profile.
b) Transducer: It is a sensor that takes generator terminal voltage as an input signal then filters it and rectifies to a dc value and finally a comparison with the reference value is done

which represents desired terminal voltage.
c) Transient Gain Reduction (TGR): To retain stability, TGR at a high frequency is used to reduce gain. But this block is not compulsory when PSS block is considered.

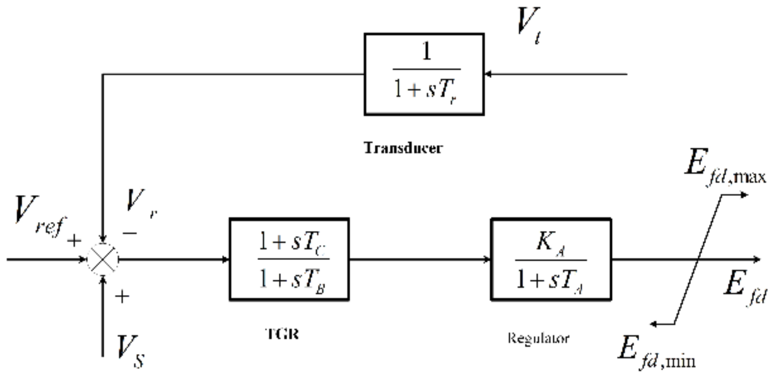

Figure 2.1: Excitation system block diagram

The model for static excitation system is represented as:

$$T_A \frac{dE_{fd}}{dt} = K_A(V_{ref} + V_s - V_r) - E_{fd}, \tag{2.1}$$

$$T_r \frac{dV_r}{dt} = V_t - V_r, \tag{2.2}$$

where E_{fd} is the field excitation voltage, V_t is the terminal voltage, T_r is the voltage transducer time constant, V_r is the filtered voltage,K_A is the regulator gain, V_{ref} is the voltage reference and T_A is the regulator time constant.

2.1.2 Power System Stabilizer (PSS)

Power System Stabilizer is used to stabilize local modes in the power system by taking local signal as feedback and is fed to excitation system. It is quite effective way to enhance the stability of system as it introduces damping torque to damp local oscillations. PSS usually take frequency, speed or power as feedback. PSS is represented by a block diagram shown in Fig.(2.2) below [13]. PSS constitutes three blocks
a) Stabilizer Gain (K_{STAB}): It is a gain that is provided to know the amount of damping via

PSS. This gain must be for maximum damping ideally but it is limited by other conditions.
b) Phase Compensation: There is phase lag between generator electrical torque and exciter input. In order to compensate this phase lag, phase compensation block is used to provide a phase lead.
c) Washout filter: It behaves as high-pass filter, with high enough value of time constant T_W so that signals associated with the oscillations in ω_r pass without any change.

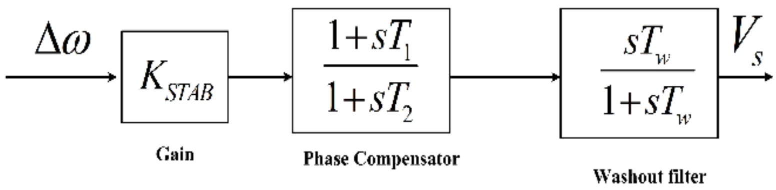

Figure 2.2: Power System Stabilizer-functional block diagram

The PSS model can be represented as:

$$G(s) = K_{pss} . \frac{sT_w}{1 + sT_w} . \frac{1 + sT_1}{1 + sT_2} \tag{2.3}$$

2.1.3 Load and Network Interface

Load can be static or dynamic. It is difficult to model it as the nature of load is unclear. Load is modeled either based on constant current or constant power or on a constant impedance model. In constant impedance model, real and reactive power both are proportional to the square of magnitude of voltage. This model is static in nature. Here, such type of model is considered for stability studies.

2.2 Modal Analysis

In order to synthesize controller, power system is required to be a linear, time invariant model. Then this system around the equilibrium points is linearized by singular perturbation theory[13]. The nonlinear system can be usually represented as

$$x = f(x, u, t) \tag{2.4}$$

$$y = h(x, u, t) \tag{2.5}$$

here x, y and u are state , output and input vector respectively. f and h are non-linear functions of x, u and t(time).
Now, if the system is independent of time then the time-invariant system is represented by

$$x = f(x, u) \tag{2.6}$$

$$y = h(x, u) \tag{2.7}$$

Linearization of power system is done around equilibrium point which can be obtained from load flow. Let the equilibrium point be denoted as (x_0, u_0). The linear model is

$$\Delta \dot{x} = A\Delta x + B\Delta u \tag{2.8}$$

$$\Delta y = C\Delta x + D\Delta u \tag{2.9}$$

where A is a state matrix, B is an input matrix, C is an output matrix. Nontrivial solution values represent eigenvalues of A matrix and is obtained from

$$A\phi = \lambda\phi \tag{2.10}$$

$$det(A - \lambda I) = 0 \tag{2.11}$$

The behavior of states can be understood by studying the eigenvalues in the form of $\sigma \pm j\omega$ obtained from above equation. σ signifies stability of system ie. when σ is positive, system is unstable and vice versa. Mode frequency and damping ratio are obtained by $f = \frac{\omega}{2\pi}$; $\zeta = \frac{-\sigma}{\sqrt{\sigma^2 + \omega^2}}$ respectively.
For every eigenvalue (λ_i), a column vector exists (ϕ_i) which satisfies an equation below and is called Right eigenvector.

$$A\phi_i = \lambda_i \phi_i \tag{2.12}$$

Right eigenvector is used to give information about Mode Shape. When a particular mode is excited then the relative activity of a state variable is called Mode shape. An element ϕ_{ki} of the right eigenvector ϕ_i gives the amount activity of a state variable (x_k) in an i^{th} mode.

Left eigenvector ψ_i satisfies the equation below. It gives the combination of state variables that displays i^{th} mode

$$\psi_i A = \lambda_i \psi_i \tag{2.13}$$

Relative participation os state in a mode can be measured by Participation Factor. Participation factor helps in to identify a mode whether it is local or inter-area. It can be termed by an element $p_{ki} = \phi_{ki}\psi_{ki}$. The activity of x_k variable in i_{th} mode is given by ϕ_{ki}. Contribution to the mode of this activity is given by ψ_{ki}. In total the product of both ϕ_{ki} and ψ_{ki} gives net participation. The i^{th} column of P matrix is given by

$$P_i = \begin{bmatrix} \phi_{1i}\,\psi_{i1} \\ \phi_2\,\psi_{i2} \\ . \\ . \\ . \\ \phi_{ni}\,\psi_{in} \end{bmatrix}$$

2.3 Loop Selection Index (LSI)

Power system model consists of multiple inputs and outputs. If we consider all input-output pairs to damp inter-area mode, then it would become complex. Also installation of PMUs for each pair will result in high cost. So Wide-Area loop selection is done to select a particular pair of input-output that corresponds to damp inter-area mode. Geometric approach for LSI method is the most effective method [8] as it is unaffected even after scaling of eigenvector. It is based on alignment of input or output vectors to the corresponding eigenvector for a particular mode.

$$LSI_{mn} = \frac{\left|b_m^T\, v_l\right| |c_n\, v_r|}{\|b_m\| \|v_l\| \|c_n\| \|v_r\|}$$

LSI_{mn} is Loop Selection Index related to n^{th}output and m^{th} input combination, c_n is the output vector and b_m is the input vector corresponding to n^{th} output and m^{th} input respectively. v_r and v_l are the right and left eigenvector of the inter-area mode.

2.4 Model Order Reduction

Electrical power systems has large number of states due to bulkiness of the system and so the order is too high. The order of controller needed to design for such system and computation time, both are high. So to address this problem, order reduction of plant must be done. Order reduction can be done through via schur method or via balanced model truncation via square root method or hankel norm method [12]. One has to reduce model such that it retains the input-output behavior as the original model over a desired frequency range.

Balancmr returns a reduced order model G_r of G and a struct array redinfo containing the error bound of the reduced model and Hankel singular values of the original system. The error bound is computed based on Hankel singular values of G. These values indicate the respective state energy for a stable system. Hankel reduction method guarantees an error bound on the infinity norm of the additive error $\|G - G_r\|_\infty$ for well-conditioned model reduced problems.

$$\|G - G_r\|_\infty \leq 2 \sum_{k+1}^{n} \sigma_i$$

is additive error bound. This method is similar to the additive model reduction balancmr and schurmr, but actually it can produce more reliable reduced order model when the desired reduced model has nearly controllable and/or observable states.

2.5 Chapter Summary

The modeling of power system and analysis for small signal stability studies is briefly explained in this chapter. PSS is used to damp local oscillations. Modal analysis is done to evaluate system behavior. To reduce the cost of installation of many PMUs, wide area loop selection is discussed. Lastly, as the model order was very high and due to that it takes large computation time to design controller, so Hankel norm method is used to reduce model order.

CHAPTER 3

Simple Wide-Area Controller Design for Damping of Inter-Area Oscillations

3.1 Introduction

After the modeling, linearizing and identifying oscillatory modes of the system, controller is to be designed to damp the oscillations. As PSS is able to damp local oscillations, so now we should design such a controller which can damp inter-area oscillations. Wide Area Damping Controller method is introduced to cope up with this problem.

A system is vulnerable to noise, disturbance and also always a difference between actual system and the system modeled exist. Thus in a control system design, robustness is most essential to be attained. So typically a controller must be designed to stabilize system and achieve robustness. Controller generates a damping torque to compensate phase lag between AVR and machine in order to align torque in the direction of $\Delta\omega$. A WDC which is designed taking into consideration of a weak line situation, in other situations it may not work uniformly. This is because synchronizing torque increase when line reactance increase, and frequency of oscillation increase along with phase lead requirement. So, robust control technique is required to combine during the designing. Even with an uncertainty in a system, Robust control technique provides stability and good performance . Among all the methods discussed during power system stability studies, H_∞ based mixed sensitivity method is very popular.

3.2 Consideration of Delays

The term inter-area defines the difference between two signals of different area. So, it is viewed as the difference of speed between i^{th} and j^{th} generator from two different areas ($\Delta\omega_{ij} = \Delta\omega_i - \Delta\omega_j$) [2]. Now, time-synchronization is required between these two signals. When both signals are to be synchronized then equal amount of delays must exist and for non-synchronized with almost no delay in local signal, unequal amount of delays are taken. In Fig.(3.1), when non-synchronized then the switch S is placed at 1 and for synchronization of both signals, switch S must be placed at 2. Time delay is modeled by 2^{nd} order Pade approximation as it reasonable good to handle delay.

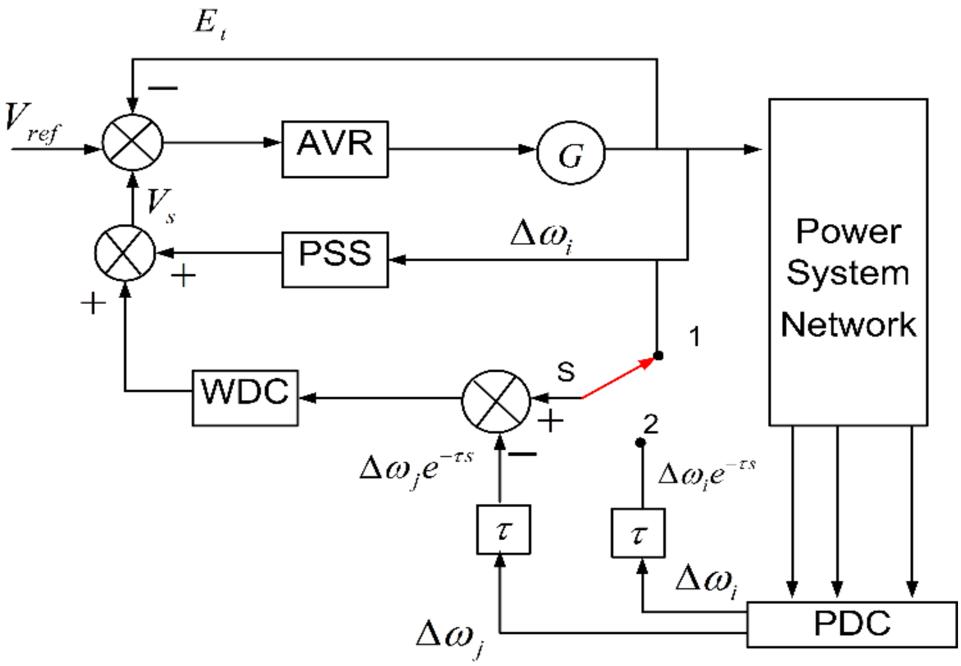

Figure 3.1: Wide-Area Control Structure

Different types of feedback configuration [17]:

Synchronous Feedback: Here the switch S at 2 in Fig.(3.1), so it provides equal amount of delay for both local and remote signal represented by Fig.(3.2).

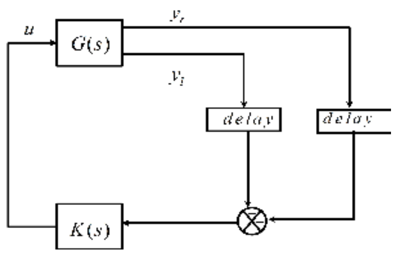

Figure 3.2: Synchronous feedback block diagram

Non-Synchronous Feedback: Here the switch S at 1 in Fig.(3.1), so it provides unequal amounts of delay for both remote and local signal. Local signal delay is negligible and delay is observed in remote signal only. It is represented in Fig.(3.3).

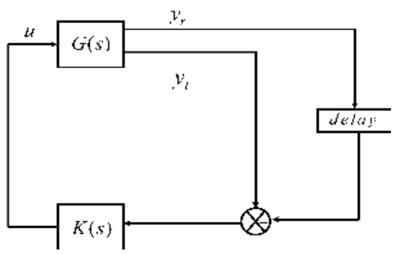

Figure 3.3: Non-Synchronous feedback block diagram

where y_r and y_l are remote and local signals respectively.

3.3 H_∞ mixed-sensitivity formulation

H_∞ space corresponds to transfer function which has no right half plane poles. So, it is stable in nature. The objective of H_∞ control is to minimize H_∞ norm of closed-loop transfer function related to performance and stability. A norm is a size of a signal or s system and is used as a measure for performance [24].

A generalized control structure of a plant is shown in Fig.(3.4). Controller should have the property to reject the disturbances and for good feedback action it should be less sensitive to noise or be able to attenuate the effect of noise. From Fig.(3.4) it can be written as in [1],

$$y = (1 + GK)^{-1}Gd + GK(1 + GK)^{-1}n, \tag{3.1}$$

where $S = (1 + GK)^{-1}$ and $T = GK(1 + GK)^{-1} = 1 - S$ and S is called as sensitivity

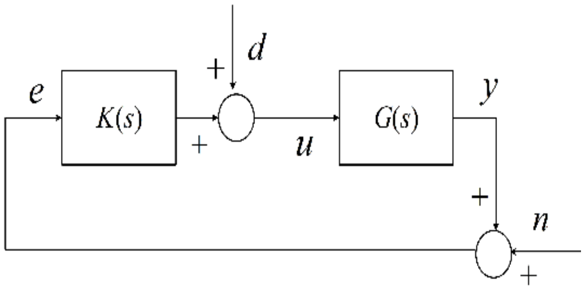

Figure 3.4: Generalized Control Plant

function and T is closed transfer function or complimentary sensitivity function. S is the transfer function of output to disturbance.

Disturbance and noise can lead system to instability. So there is a need to find a robust controller that disturbance and noises are minimized. For good disturbance rejection, H_∞ norm of S should be minimum. To optimize the control effort within a bandwidth, H_∞ norm of KS should be minimum. So, minimization problem is

$$\min_{K \in \mathbb{S}} \left\| \begin{bmatrix} S \\ KS \end{bmatrix} \right\|_\infty \tag{3.2}$$

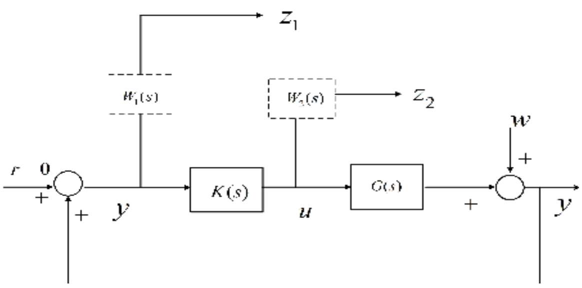

Figure 3.5: Mixed-sensitivity formulation

But minimization of both KS and S over whole frequency spectrum is not possible simultaneously. Rejection of disturbance is usually needed at low frequency range, so at low frequency S can be minimized. Control action requirement is limited at a higher frequency, so KS can be minimized at high frequency range. So appropriate weights are selected to minimize both S and KS. $W_1(s)$ acts as s low pass filter for disturbance rejection at low frequency and $W_2(s)$ is a high pass filter in order to reduce control effort at higher frequency range. After weights are introduced, the problem is restated as:

Find a stabilized controller K such that

$$\min_{K\in\mathbb{S}} \left\| \begin{bmatrix} W_1 S \\ W_2 K S \end{bmatrix} \right\|_\infty < 1 \tag{3.3}$$

3.4 Generalized H_∞ problem with pole-placement

The mixed-sensitivity problem can be solved by converting it into a generalized H_∞ problem [1]. For simplicity at first W_1 and W_2 weights are ignored. Without the weights the Figure(3.5) can be redrawn in Figure (3.6) in terms of the A,B,C matrices of the system. It is assumed that D=0. From Figure(3.6), it can be observed that

$$\dot{x} = Ax + Bu; \;\; z_1 = Cx + \omega; \;\; z_2 = u; \;\; y = Cx + \omega \tag{3.4}$$

where x: state variable vector, w: disturbance input, u: control input, y: measured output, z: regulated output.

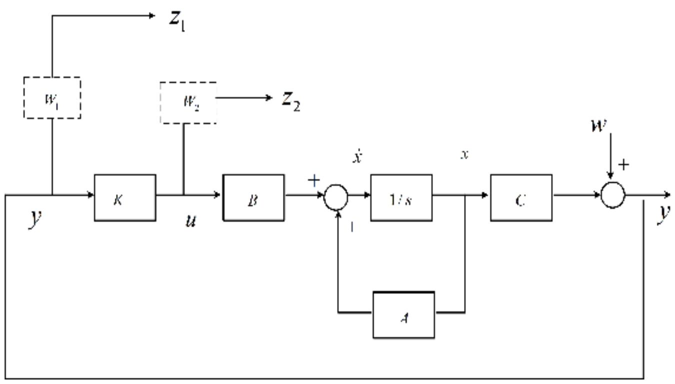

Figure 3.6: Generalized regulator set-up for mixed-sensitivity formulation.

Now the effect of the weighting filters are included in the generalized regulator. After formulation of generalized regulator, a control law $u = K(s)\,y$ is to be found out for some H_∞ performance index $\gamma > 0$, such that : $T_{wz\infty} < \gamma$. where $T_{wz}(s)$ is the closed-loop transfer function w to z. If the LTI controller is represented as:

$$\dot{x}_k = A_k x_k + B_k y \tag{3.5}$$

$$u = C_k x_k + D_k y \tag{3.6}$$

then the closed-loop transfer function $T_{wz}(s)$ is given by $T_{ws}(s) = D_{cl} + C_{cl}\left(SI - A_{cl}\right)^{-1} B_{cl}$

where,
$A_{cl} = \begin{bmatrix} A + B_2 D_k C_2 & B_2 C_k \\ B_k C_2 & A_k \end{bmatrix}$, $B_{cl} = \begin{bmatrix} B_1 + B_2 D_k D_{21} \\ B_k D_{21} \end{bmatrix}$, $C_{cl} = \begin{bmatrix} C_1 + D_{12} D_k C_2 & D_{12} C_k \end{bmatrix}$,

$D_{cl} = D_{11} + D_{12} D_k D_{21}$

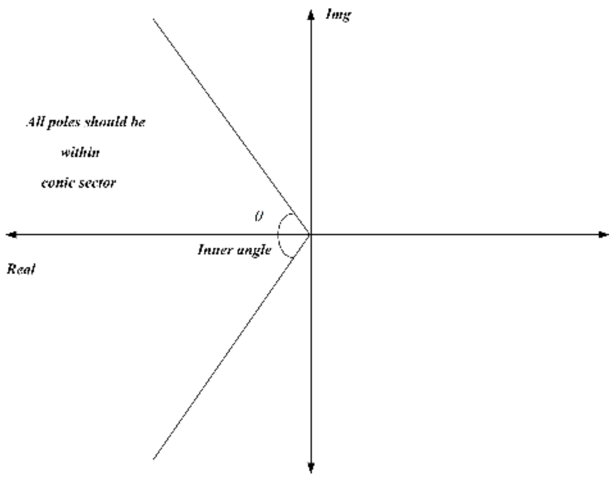

Figure 3.7: The region of pole placement

Along with the robustness obtained from $T_{wz\propto} < \gamma$, another requirement is to have oscillations damp within 10-15 secs. This criteria can be achieved if closed-loop poles are in a region in the left half complex plane. So find a control law $u = K(s)\,y$ such that:
1.$\|T_{wz}\|_{\infty} < \gamma$
2. Poles of the closed-loop system lie in a desired region.

The desired region can be a disk, conic sector, vertical/ horizontal strips etc. A conic sector with apex at origin and inner angle θ is an appropriate region as it ensures minimum damping ratio $\varsigma_{\min} = \cos^{-1}\frac{\theta}{2}$.

The above objective can be rewritten in the LMI (Linear Matrix Inequality) form as it more simpler and can be used as multi-objective control in the framework [7][20]. It avoids cancellation of pole-zero and help in obtaining a low order controller.

3.5 Chapter Summary

The chapter represents the control theory for the synthesis of controller to stabilize the power system. Delay of feedback signal was then considered with two different conditions which is synchronous and non-synchronous form. Next, H_{∞} objective was then discussed and in this discussion, weights were included to reduce control effort and for disturbance rejection. H_∞ approach handle frequency domain specification but lack control over transient performance. So, regional pole placement objective was included to overcome this issue. At last, the whole design procedure is presented in stepwise manner.

CHAPTER 4

Fault Tolerant Wide-Area Controller Design for Damping of Inter-Area Oscillations

4.1 Introduction

Wide-Area Damping Controller is designed above considering the case of no faults or loss of sensors. However, a fault of sensor units (loss of remote signals) may occur, which may deteriorate the performance of system due to a lack of remote feedback signal which used to damp inter-area oscillations via WAC. This attracts the study of fault-tolerant control (FTC) as an area of research. The main objective of FTC is to design a controller which can handle abnormal conditions and retain whole system stability with acceptable performance. Several approaches have been done in this theory, but LMI approach was found relatively simple and thus it is popular approach in this field.

In FTC theory, two approaches exist: active and passive FTC [22]. The controller is reconfigured in active FTC whenever a fault is detected, whereas controller is fixed in passive FTC and is obtained by a priori design based on fault models. In this thesis, we discuss fault-tolerance for four machine eleven bus system with passive FTC method approach.

4.2 Control Design Formulation

Consider an LTI system [21]

$$\dot{x}(t) = Ax(t) + Bu(t), \quad y(t) = Cx(t), \quad G(s) \overset{s}{=} \left[\begin{array}{c|c} A & B \\ \hline C & D \end{array}\right] \tag{4.1}$$

where state vector $x \in R^n$, input vector $u \in R^q$ and output vector $y \in R^p$. State matrices $A \in R^{n\times n}$, input matrix $B \in R^{n\times q}$ and output matrix $C \in R^{p\times n}$ of the system. C matrix is described as

$$C = [\begin{array}{ccccc} c_1^T & c_2^T & ... & c_{p-1}^T & c_p^T \end{array}]^T \tag{4.2}$$

where $c_j \in R^{1\times p}$ is j^{th} output.Here $p \geq 2$, one local and at least one remote signal is used. Below family of plants represent sensor faults

$$\dot{x}(t) = Ax(t) + Bu(t), \quad y_i(t) = C_i x(t), \quad G_i(s) \overset{s}{=} \left[\begin{array}{c|c} A & B \\ \hline C_i & D \end{array}\right] \tag{4.3}$$

where, for $i = \ 0, 1, ..., p-1$ and $j = \ 0, 1, ..., p-1$.

$$C = [\begin{array}{ccccc} c_1^{iT} & c_2^{iT} & ... & c_{p-1}^{iT} & c_p^T \end{array}]^T, \quad c_j^i = \begin{Bmatrix} 0 & if \ i = j \\ c_j & if \ i \neq j \end{Bmatrix}$$

Here c_p is local signal and is an assumption is taken of its availability always. At normal condition output matrix is $C_0 = [\begin{array}{ccccc} c_1^T & c_2^T & ... & c_{p-1}^T & c_p^T \end{array}]^T = C$ with $i = 0$. Suppose there is a loss of second sensor i.e. $i = 2$, then C matrix is $C_2 = [\begin{array}{ccccc} c_1^T & 0 & ... & c_{p-1}^T & c_p^T \end{array}]^T$. For simplicity, one remote signal loss is considered at one time but it can be generalized for loss of more than one.

4.2.1 Conventional Control

A CC satisfies a desired level of performance when both local and remote signals are available. However, it can deteriorate performance significantly when a sudden loss of remote signals occurs. LMI approach with regional pole placement method is used to design CC. Same method is used to design FTC to have a fair comparison between CC and FTC.
The controller is represented as:

$$\dot{x}_c(t) = A_c x_c(t) + B_c y(t), \quad u(t) = C_c x_c(t), \quad K_c(s) \overset{s}{=} \left[\begin{array}{c|c} A_c & B_c \\ \hline C_c & 0 \end{array}\right] \tag{4.4}$$

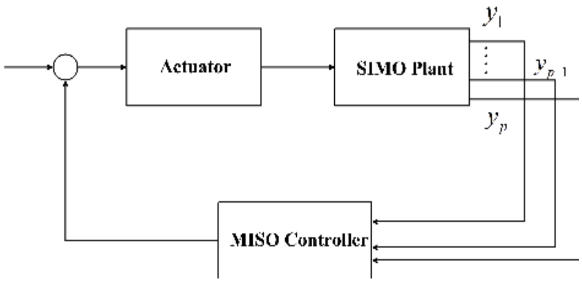

Figure 4.1: General control formulation-wide area signals subject to faults

with $A_c \in R^{n\times n}$, $B_c \in R^{n\times p}$, $C_c \in R^{q\times n}$ Now closed-loop dynamics is written as $\dot{\widetilde{x}} = \widetilde{A}\widetilde{x}$ where

$$\widetilde{A} = \begin{bmatrix} A & BC_c \\ B_cC & A_c \end{bmatrix} \tag{4.5}$$

The objective is to place eigenvalues in desired conic region and following theorem describes the objective.

Theorem

The matrix $\widetilde{A}$ is stable and all its eigenvalues lie in a desired region if there exist $\widetilde{P}$ (symmetric matrix) such that

$$\widetilde{P} > 0 \tag{4.6}$$

$$\begin{bmatrix} sin\theta(\widetilde{P}\widetilde{A} + \widetilde{A}^T\widetilde{P}) & cos\theta(\widetilde{P}\widetilde{A} - \widetilde{A}^T\widetilde{P}) \\ cos\theta(\widetilde{A}^T\widetilde{P}) - \widetilde{P}\widetilde{A}) & sin\theta(\widetilde{P}\widetilde{A} + \widetilde{A}^T\widetilde{P}) \end{bmatrix} < 0 \tag{4.7}$$

where θ is inner angle of conic region.
Another objective is to limit control effort. This is achieved by minimizing the transfer function between the disturbance output d and the input u. So the objective is to minimize γ_c

$$\left\| K_c(I - GK_c)^{-1} \right\|_\infty < \gamma_c \tag{4.8}$$

with

$$K_c(I - GK_c)^{-1} \stackrel{s}{=} \left[\begin{array}{c|c} \widetilde{A} & \widetilde{B} \\ \hline \widetilde{C} & 0 \end{array} \right] \tag{4.9}$$

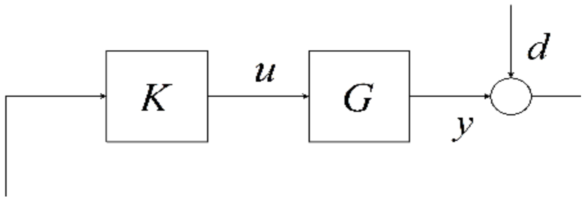

Figure 4.2: Control loop with disturbance at plant output

where $\widetilde{A} \in R^{2n \times 2n}$ in (4.5) and $\widetilde{B} \in R^{2n \times p}$ and $\widetilde{C} \in R^{p \times 2n}$ are given as

$$\widetilde{B} = \begin{bmatrix} 0 \\ B_c \end{bmatrix} \qquad \widetilde{C} = \begin{bmatrix} 0 & C_c \end{bmatrix} \tag{4.10}$$

Applying Bounded Real Lemma [7] on (4.8), then it is formulated in a matrix inequality below

$$\begin{bmatrix} \widetilde{P}\widetilde{A} + \widetilde{A}^T\widetilde{P} & \widetilde{P}\widetilde{B} & \widetilde{C}^T \\ \widetilde{B}^T\widetilde{P} & -\gamma_c I & 0 \\ \widetilde{C} & 0 & -\gamma_c I \end{bmatrix} \tag{4.11}$$

The problem is bilinear and the nonlinearities can be removed by some change of controller variables. The required change is defined in terms of Lyapunov matrix $\widetilde{P}$ and its inverse

$$\widetilde{P} = \begin{bmatrix} X & U \\ U^T & X_c \end{bmatrix} \qquad \widetilde{P}^{-1} = \begin{bmatrix} Y & V \\ V^T & Y_c \end{bmatrix} \tag{4.12}$$

with $X, Y, V, U \in R^{n \times n}$. From $\widetilde{P}\widetilde{P}^{-1} = I$,

$$UV^T = I - XY \tag{4.13}$$

Here $\widetilde{P}$ satisfies the identity

$$\widetilde{P}\Pi_2 = \Pi_1 \tag{4.14}$$

where

$$\Pi_1 = \begin{bmatrix} X & I \\ U^T & 0 \end{bmatrix}, \qquad \Pi_2 = \begin{bmatrix} I & Y \\ 0 & V^T \end{bmatrix} \tag{4.15}$$

Post and Pre multiply (4.6), (4.7) and (4.11) by matrices

$$\Pi_2, \quad \begin{bmatrix} \Pi_2 & 0 \\ 0 & \Pi_2 \end{bmatrix}, \quad \begin{bmatrix} \Pi_2 & 0 & 0 \\ 0 & I & 0 \\ 0 & 0 & I \end{bmatrix} \tag{4.16}$$

and their transposes respectively.
After doing the product and applying change of variables below,

$$\hat{C}_c = C_c V^T, \quad \hat{B}_c = U B_c, \quad \hat{A}_c = XAY + XB\hat{C}_c + \hat{B}_c CY + UA_c V^T \tag{4.17}$$

(4.6), (4.7) and (4.11) become linear. The respective linear LMI is represented below

$$\begin{bmatrix} X & I \\ I & Y \end{bmatrix} > 0 \tag{4.18}$$

$$\begin{bmatrix} sin\theta L_{11} & cos\theta L_{12} \\ cos\theta L_{12}^T & sin\theta L_{11} \end{bmatrix} < 0 \tag{4.19}$$

where

$$L_{11} = \begin{bmatrix} XA + A^T X + C^T \hat{B}_c^T + \hat{B}_c C & \hat{A}_c + A^T \\ \hat{A}_c^T + A & AY + YA^T + B\hat{C}_c + \hat{C}_c^T B^T \end{bmatrix} \tag{4.20}$$

$$L_{12} = \begin{bmatrix} XA - A^T X + \hat{B}_c C - C^T \hat{B}_c^T & \hat{A}_c - A^T \\ A - \hat{A}_c^T & AY - YA^T + B\hat{C}_c - \hat{C}_c^T B^T \end{bmatrix} \tag{4.21}$$

$$\left[\begin{array}{cc|cc} \multicolumn{2}{c|}{\multirow{2}{*}{L_{11}}} & \hat{B}_c & 0 \\ & & 0 & \hat{C}_c^T \\ \hline \hat{B}_c^T & 0 & -\gamma_c & 0 \\ 0 & \hat{C}_c & 0 & -\gamma_c \end{array}\right] < 0 \tag{4.22}$$

To calculate the controller $K_c(s)$, the algorithm is

- Define $Z = I - XY$
- Find SVD (Singular Value Decomposition) $[u, \sigma, v]$=svd$\{Z\}$
- Find $U = u\sqrt{\sigma}$ and $V = v\sqrt{\sigma}$
- Calculate A_c, B_c and C_c using (4.17) and finally $K_c(s)$ is given by (4.4).

4.3 Passive-Fault Tolerant Control

An FTC is required to achieve desired performance both when local and remote signals are available and also in a situation when there is a loss of remote signals.

4.3.1 Iterative procedure for passive FTC

In passive FTC [21], the problem is to synthesize a single controller and should work in both normal and faulty conditions. State space representation and closed -loop dynamics of FTC$_p$ are given by (4.4) and (4.5). The controller is designed for family of plants (4.3) such that

$$u(s) = K_f(s)y_0(s), ..., u(s) = K_f(s)y_p(s).$$

The objective is to have eigenvalues of $\widetilde{A}$ for $i = 0, 1, ..., p$ lie in conic region. The constraints are same as in (4.6) and (4.7) and θ_i is the inner angle of conic region for the i^{th} system.

The algorithm have an advantage of being linear but they have a drawback - the matrix C_f value is found and is fixed to $\hat{C}_c Y^{-1}$ before calculating other control matrices. Also value of A_f and B_f depends on C_f. So it may not be possible to have solution for specific value of C_f but one may exist for other values. To avoid this problem, and iterative procedure is used and it significantly improves damping.

Same Transformations are applied to only (4.6) and (4.7) as in CC, it is found that same change of variables in (4.17) cannot be performed to linearize the inequalities. This problem is due to multiple systems corresponding to different possible fault scenarios. So transformation is applied with following change of variables

$$\hat{C}_c = C_f V^T, \quad \hat{B}_c = UB_f, \tag{4.23}$$

$$\hat{A}_c = XAY + XB\hat{C}_c + UA_f V^T \tag{4.24}$$

So after transformation, the LMI obtained is

$$\begin{bmatrix} X & I \\ I & Y \end{bmatrix} > 0 \tag{4.25}$$

$$\begin{bmatrix} sin\theta_i L_{11}^i & cos\theta_i L_{12}^i \\ * & sin\theta_i L_{11}^i \end{bmatrix} < 0 \tag{4.26}$$

for all i, where

$$L_{11}^{i} = \begin{bmatrix} XA + A^T X + C_i^T \hat{B}_c^T + \hat{B}_c C_i & A^T + \hat{A}_c + \hat{B}_c C_i Y \\ * & AY + YA^T + B\hat{C}_c + \hat{C}_c^T B^T \end{bmatrix} \tag{4.27}$$

$$L_{12}^{i} = \begin{bmatrix} A^T X - XA + C_i^T \hat{B}_c^T - \hat{B}_c C_i & A^T - \hat{A}_c - \hat{B}_c C_i Y \\ * & YA^T - AY + \hat{C}_c^T B^T - B\hat{C}_c \end{bmatrix} \tag{4.28}$$

Here, the inequality in (4.26) is due to term $\hat{B}_c C_i Y$ in blocks of (4.27) and (4.28). As open-loop is stable, it is possible to fix a value to $\hat{B}_c$ or Y and run the iterative algorithm. For a variable Z, let k denote iteration number then $Z(k)$ denotes iteration value of Z at iteration k.

Iterative algorithm

(i) Set $k = 1$ and $\hat{B}_c(k) = 0$, so that (4.26) becomes linear.

(ii) Find minimum value of $\theta_i(k)$ (go on reducing angle of conic region to shift modes to left-hand side of complex plane such that feasible solution exists for (4.25) and (4.26)). Find $Y(k), X(k), \hat{C}_c(k), \hat{A}_c(k)$ and set $Y(k+1) = Y(k)$.

(iii) Put $k = k + 1$

(iv) Find minimum value of $\theta_i(k)$ (go on reducing angle of conic region to shift modes to left-hand side of complex plane such that feasible solution exists for (4.25) and (4.26)). Find $X(k), \hat{B}_c(k), \hat{C}_c(k), \hat{A}_c(k)$ and set $\hat{B}_c(k+1) = \hat{B}_c(k)$.

(v) Put $k = k + 1$ and go to (ii).

The iteration terminates when

$$\theta_i(k) - \theta_i(k+1) \leq \in \tag{4.29}$$

where $\in$ is small value (10^{-3}) and $\theta_i(k+1) \leq \theta_i(k)$. When (4.29) is satisfied then controller elements A_f, B_f and C_f are calculated from (4.25) and (4.26). Note, we have used linear approximation, so there is no guarantee that the solution will converge to the optimal solution but it gives improvement to the damping ratio.

4.4 Chapter Summary

In this chapter, the control design for family of plants if formulated corresponding to normal and different faulty conditions. First, Conventional Control theory is presented and LMI conditions are obtained by transformation and change of variables of matrices. Then the controller for CC is calculated but CC degrades its dynamic performance when fault occurs. So to overcome this problem, passive FTC controller is designed in a similar method as in CC but with different change of variables. FTC_p improves damping ratio but optimal solution is not guaranteed.

4.5 Design Steps

The design procedure on this thesis can be summarized as:

- Linearize power system model without wide-area loop.
- Through modal analysis, analyze system modes and then select a suitable feedback loop for WDC. To reduce controller computation time, reduce the model order.
- WDC Design using H_∞ control with regional pole placement.
- Estimate and include delay for both cases of synchronous and non-synchronous feedback from time-stamped PMU signals. Approximate delay using Pade 2^{nd} order approximation.
- Now redesign WDC including both type of delay feedbacks and then comparison is done for performance evaluations.
- A case of fault in the feedback is considered. CC and FTC controller design is done and compared to find the effectiveness of CC and FTC during fault.

CHAPTER 5

Case Studies

5.1 Simple Wide-Area Controller Design

5.1.1 System Description

The case study is upon the power system consisting of 4 machine 11 bus with two areas having 2 generators in each area [13]. Two areas are connected via weak tie long transmission line. The system is modeled in MATLAB Simulink to study different types of modes and how to overcome them through controllers. Generator G_1 and G_3 (i.e. one generator from each area) are equipped with a local PSS which damps out local modes significantly but less effective in damping inter-area oscillations. So the need of designing WAC is a must to damp inter-area oscillations and have output settled within 10-15 secs.

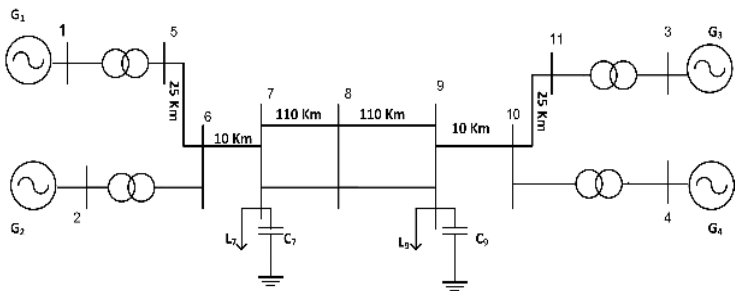

Figure 5.1: Two Area 4 machine 11 bus Power System

5.1.2 Analysis of modes

The linearization of model in Matlab is done through 'linearize' command. The linearized model order is 58^{th} order. A, B, C and D matrices of linearized plant are of the order of $A = 58 \times 58$, $B = 58 \times 4$, $C = 4 \times 58$ and $D = 4 \times 4$. The input to the model is reference voltage V_{ref} and initial power P_m. The output of the whole system can be taken as speed deviation $\Delta\omega$, rotor angle δ, electrical power etc. The outputs considered in this plant is speed deviation of all 4 generators represented by C matrix pf the linearized plant. $\Delta\omega_1$, $\Delta\omega_2$, $\Delta\omega_3$ and $\Delta\omega_4$ represents output of generators G_1, G_2, G_3 and G_4 respectively. The model is then fed to workspace of Matlab and next step is to identify modes.

Participation factor is found to identify swing modes, those states with higher participation factor corresponds to swing modes. M1, M2, and M3 modes where found to be the modes corresponding to swing modes frequency range. Figure below shows participation factor plot for M1, M2, M3 modes. Fig(5.2) for M1 mode shows that all machines are participating whereas Fig.(5.3) and (5.4) for M2 and M3 mode respectively shows that machines from Area1 ie. G_1 and G_2 and machines from Area2 ie. G_3 and G_4 participate respectively.

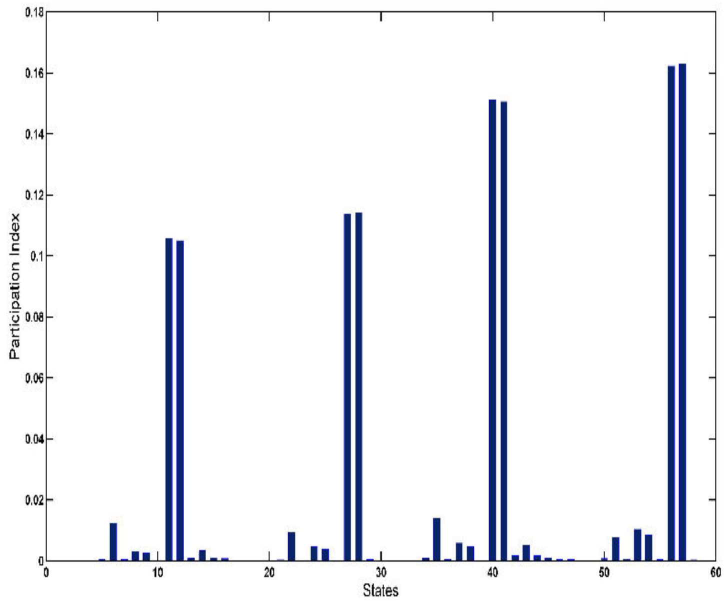

Figure 5.2: M1 mode

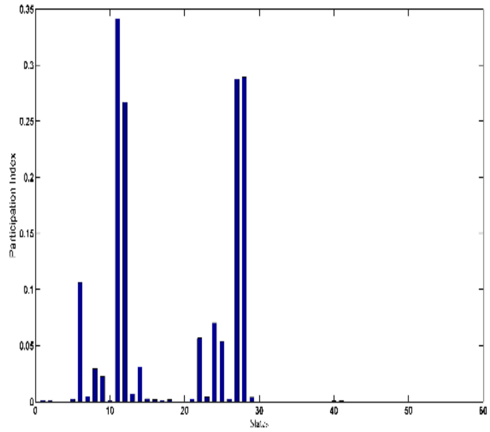

Figure 5.3: M2 mode

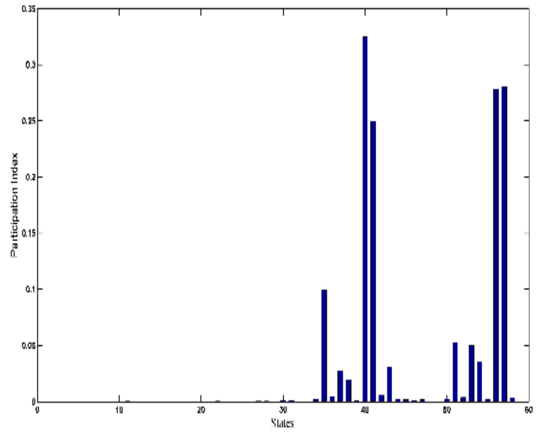

Figure 5.4: M3 mode

Figure 5.2, 5.3, 5.4 : Participation Factors of the three swing modes

Now which mode corresponds to inter-area and local mode needs to found. So mode shapes plotted via 'compass' command in Matlab. In figure below, it is shown that G1 and G2 oscillates against G3 and G4 machines, so it is an inter-area mode. For M2, figure shows that G1 and G2 oscillates against each other and for M3, G3 and G4 oscillates against each other, so both M2 and M3 are local modes.

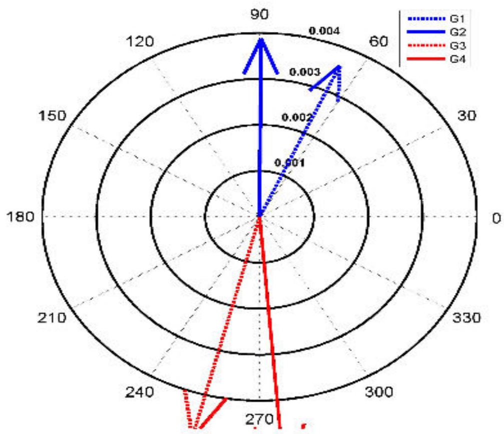

Figure 5.5: M1 inter area mode

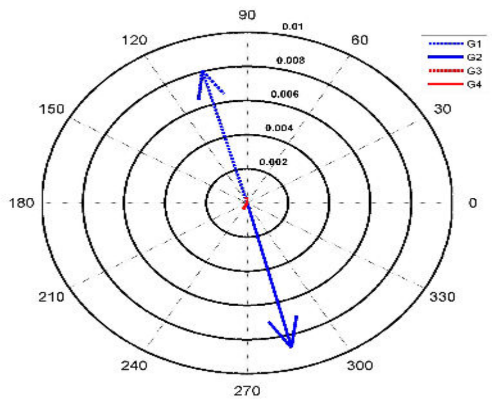

Figure 5.6: M2 local mode

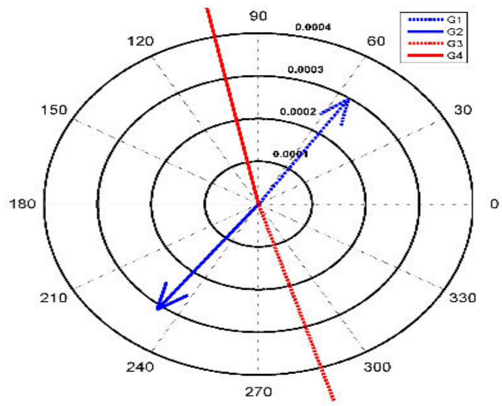

Figure 5.7: M3 local mode

Figure 5.5, 5.6, 5.7 : Mode shapes of swing modes

Table 5.1: Swing modes of the system without WDC

Mode	Mode Shape	Frequency	Damping
M1	Area1 v/s Area2	0.6227	0.08055
M2	G_1 V/s G_2	1.2106	0.2041
M3	G_3 V/s G_4	1.1394	0.2467

5.1.3 Wide-Area Loop Selection

Wide-Area Loop selection method is used to select which loop is more effective for inter-area mode. From the term inter-area means we need take feedback as difference of the speed deviation of machines of two areas ie. $\Delta\omega_{13}$, $\Delta\omega_{14}$, $\Delta\omega_{23}$, $\Delta\omega_{24}$. The calculated values of LSI are in Table(5.2). Highest LSI value corresponding to which input-output pair is checked and that loop is selected to damp inter-area mode.

Table 5.2: LSI of the IO/OP signals

	$\Delta\omega_{13}$	$\Delta\omega_{14}$	$\Delta\omega_{23}$	$\Delta\omega_{24}$
G_1	1.006	0.1064	X	X
G_2	X	X	0.1425	0.1553
G_3	0.1136	X	0.1168	X
G_4	X	0.1882	X	0.1996

From Table(5.2), it can be seen that the value corresponding to generator G_4 and speed deviation $\Delta\omega_{24}$ is the highest. So controller in the feedback takes $\Delta\omega_{24}$ as input and it is fed to generator G_4 excitation system.

5.1.4 Order Reduction of linearized plant

The linearized model of plant obtained above is of 58^{th} order. As the order is too large, the controller synthesis becomes hectic, it takes too much computation time and is complex. So in order to overcome this issue, model order reduction is done and reduced to 6^{th} order by Hankel Reduction Method. Frequency response of the reduced model must have same response as that of the original system in the desired frequency range and also retain swing modes.

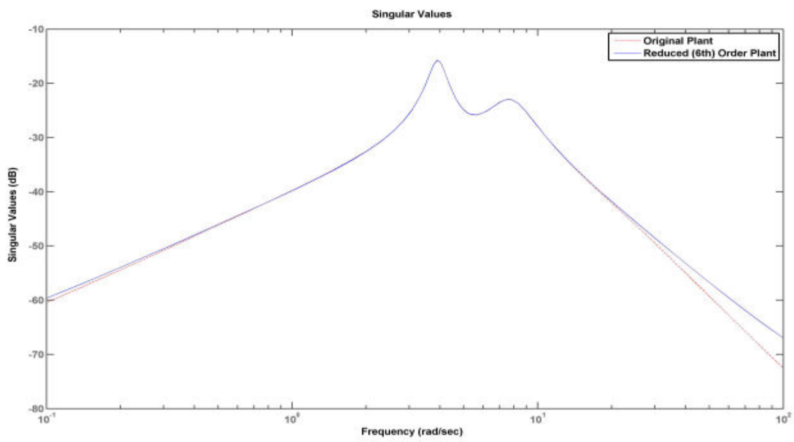

Figure 5.8: Singular value plot of full and reduced order system

5.1.5 Controller Synthesis (Without Considering Delay)

Controller is designed using reduced order model without considering delay in feedback signals at first. It is synthesized using H_∞ with regional pole-placement. Weighting functions used are $W_1 = \frac{30}{s+30}$ and $W_2 = \frac{10s}{s+100}$ as W_1 will acts as low pass filter to reject output disturbance and W_2 as a high pass filter in high frequency range to reduce control effort. Here to study inter-area mode $\Delta\omega_{24}$ is considered.

The designed controller is of 11^{th} order and then it is reduced to 4^{th} order by model order reduction method is shown in Fig.(5.9) . Now by taking controller WDC in the feedback of loop, the inter-area mode damping ratio improved from 0.08 to 0.291.

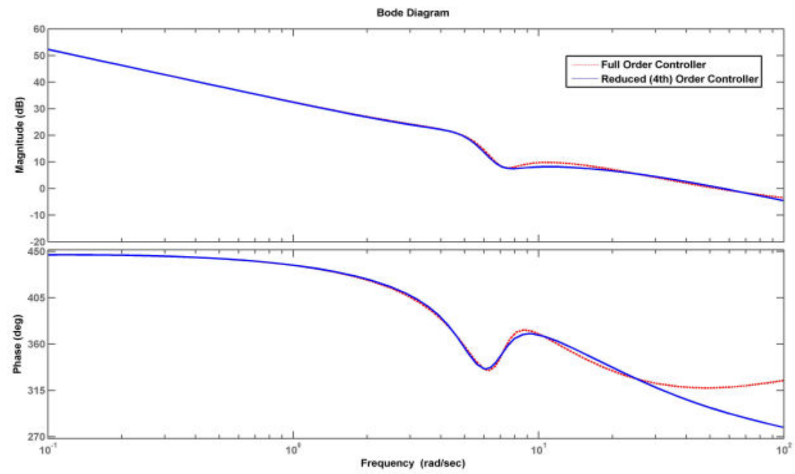

Figure 5.9: Bode plot of full order and reduced order controller

Without the wide-area loop, speed deviation $\Delta\omega_{24}$ takes more than 10 secs to get settled. However with wide-area loop, it can be seen that inter-area oscillations damp out quickly within 10 secs as shown in Fig.(5.10).

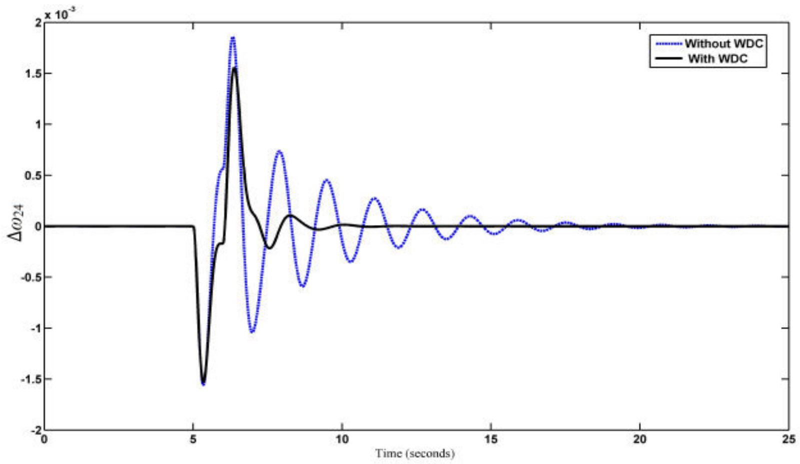

Figure 5.10: $\Delta\omega_{24}$ Plot a) without WDC b) with WDC

So we can observe significant improvement in the inter-area mode. Low sensitivity S in low frequency region showing good disturbance rejection property figure. On the other hand to ensure satisfactory performance KS is obtained low at high frequencies to reduce the control effort Fig. (5.11) and (5.12).

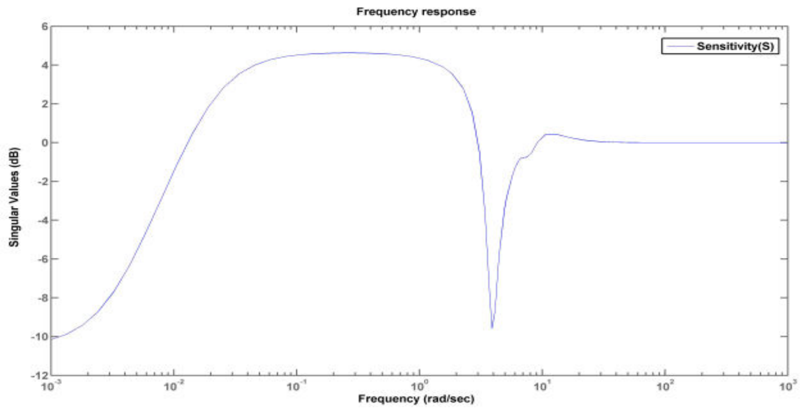

Figure 5.11: Sensitivity (S)

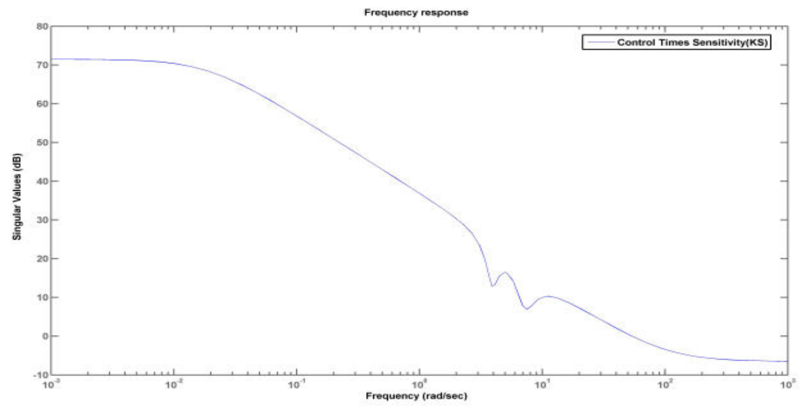

Figure 5.12: Control Times Sensitivity (KS)

5.1.6 Effect of Delay

The above system is simulated again with multiple delays in feedback signals of wide-area loop. Although system was stable robustly for different operating conditions, it loses its stability in delay in wide-area loop. Responses for different delays are checked and found that as delay increase, the system becomes unstable. First considering the delay in synchronized feedback, it is observed that the damping is reduced and system goes unstable as delay increases in Fig.(5.13). Now delay in non-synchronized feedback is considered as shown in Fig.(5.14) and here too the system goes unstable with delay value increase. For synchronous case, with different delays it is shown the settling time of local mode has increased. Though delay variations have small impact to inter-area mode but significantly effect the local modes in case of synchronous feedback. For Non-Synchronous case, the delay value used are same as in synchronous case and found that it is more stable compared to the latter.

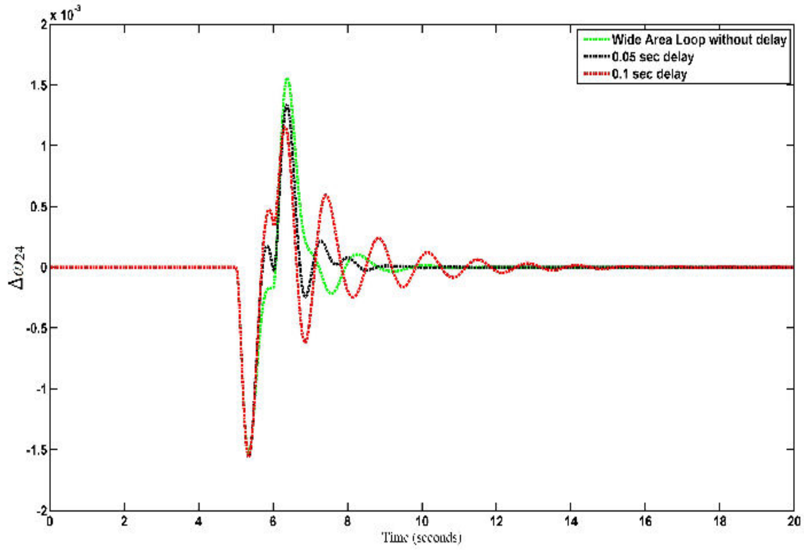

Figure 5.13: $\Delta\omega_{24}$ plot with time-delays in synchronous feedback

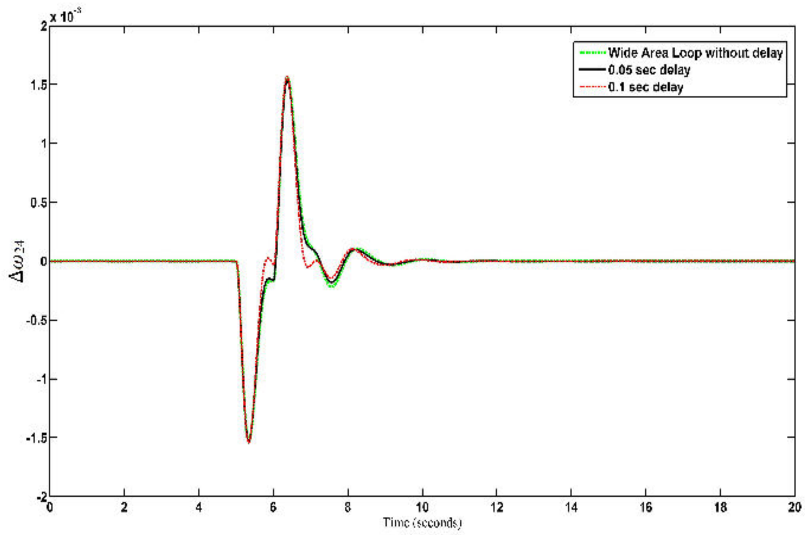

Figure 5.14: $\Delta\omega_{24}$ plot with time-delays in non-synchronous feedback

A comparison is done of system performance without WDC, with Synchronous WDC and with Non-Synchronous WDC and considering delay of 100 milliseconds in synchronous and non-synchronous delay system as shown in Fig.(5.15) and (5.16). It can be seen that Non-synchronous WDC works better than Synchronous WDC.

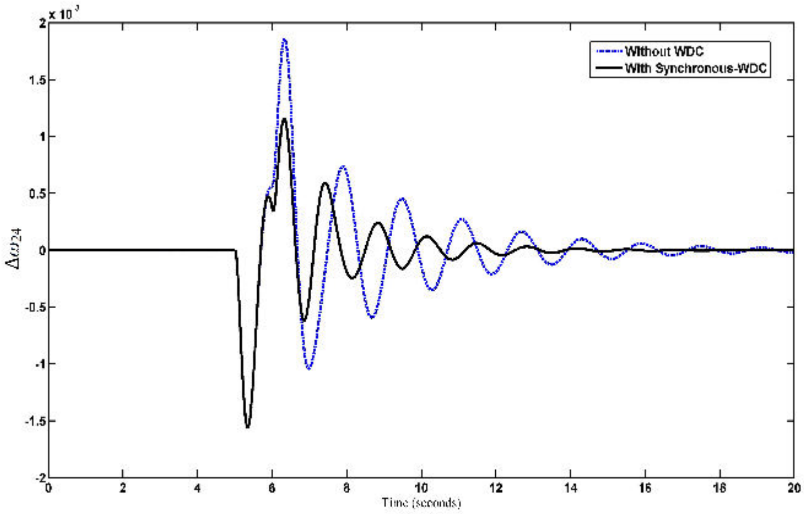

Figure 5.15: $\Delta\omega_{24}$ plot a) without WDC b) with Synchronous-WDC

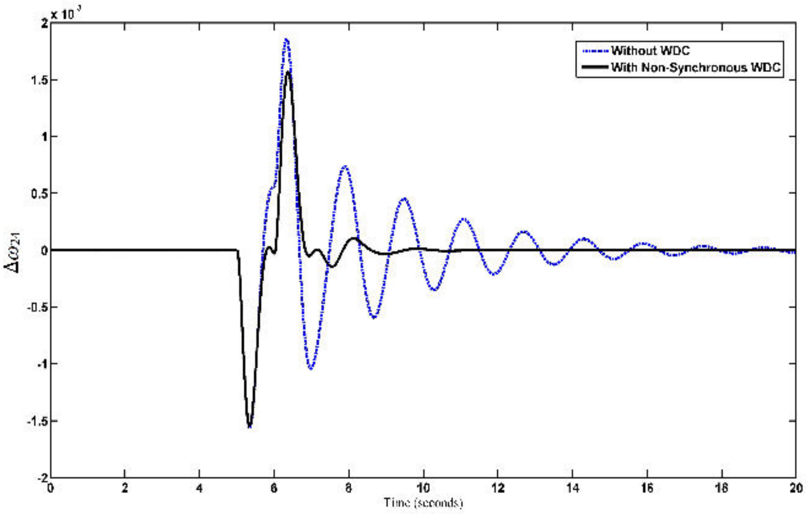

Figure 5.16: $\Delta\omega_{24}$ plot a) without WDC b) Non-synchronous WDC

5.2 Fault Tolerant Wide-Area Controller Design

5.2.1 System Description

The system used here is same as considered in wide-area control design i.e. Four Machine Eleven Bus system. The case study here is done on normal condition as before comparing to a faulty conditions i.e. loss of a remote signal. The plant is first simulated and linearized and then same weight matrices used before are added to reject disturbance and reduce control effort in high frequency range.

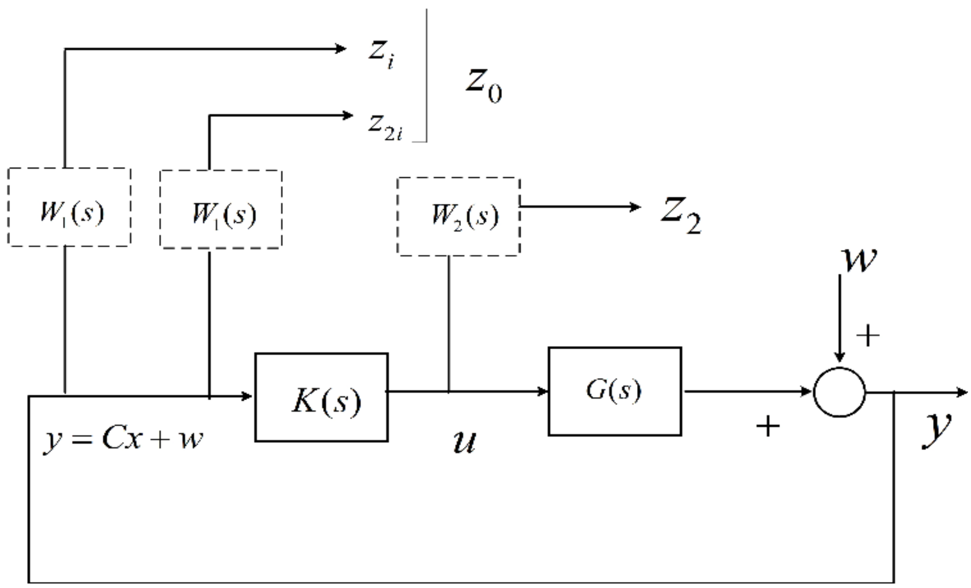

Figure 5.17: Generalized plant with weight matrices

W_1 weight matrix is added twice at same point i.e. at feedback to cope up with overall plant matrix dimension issue. The state-space representation of plant in Fig.(5.18) is given by (5.1):

$$\begin{bmatrix} \dot{x} \\ \dot{x}_0 \\ \dot{x}_3 \\ z_0 \\ z_3 \\ y \end{bmatrix} = \left[\begin{array}{ccc|c|c} A & 0 & 0 & 0 & B \\ B_{01} & A_{01} & 0 & B_{011} & 0 \\ 0 & 0 & A_3 & 0 & B_3 \\ \hline 0 & C_{01} & 0 & 0 & 0 \\ 0 & 0 & C_3 & 0 & D_3 \\ \hline C & 0 & 0 & I & 0 \end{array}\right] \begin{bmatrix} x \\ x_0 \\ x_3 \\ w \\ u \end{bmatrix} \tag{5.1}$$

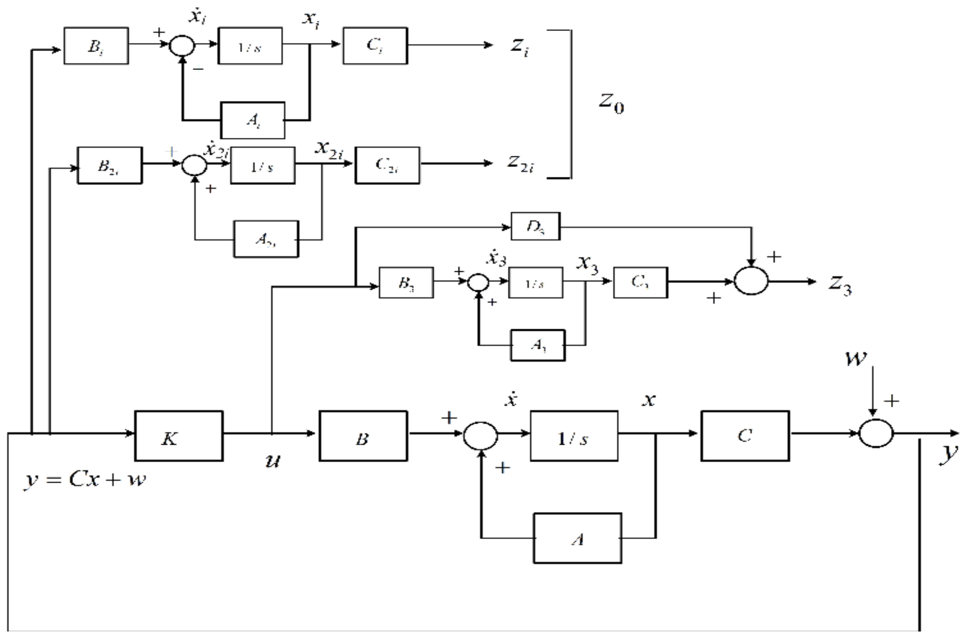

Figure 5.18: Generalized plant with weight matrices in state-space form

where $B_{011} = \begin{bmatrix} B_i & 0 \\ 0 & B_{2i} \end{bmatrix}$, $B_{01} = B_{011} * C$, $A_{01} = \begin{bmatrix} A_i & 0 \\ 0 & A_{2i} \end{bmatrix}$, $C_{01} = \begin{bmatrix} C_i & 0 \\ 0 & C_{2i} \end{bmatrix}$

Now the plant with weighted matrices (G_p) has A_p, B_p, C_p matrix as below

$$A_p = \begin{bmatrix} A & 0 & 0 \\ B_{01} & A_{01} & 0 \\ 0 & 0 & A_3 \end{bmatrix}, B_p = \begin{bmatrix} B \\ 0 \\ B_3 \end{bmatrix}, C_p = \begin{bmatrix} C & 0 & 0 \end{bmatrix} \tag{5.2}$$

here, $A_p \in R^{(n+3)\times(n+3)}$, $B_p \in R^{(n+3)\times(1)}$, $C_p \in R^{(2)\times(n+3)}$

Now the above matrix are used as plant matrices in iterative algorithm. C matrix of plant without weighted matrices represent feedback output signals. Here we consider feedback of speed deviation $\Delta\omega_{24}$ to the generator G_4 as done in WAC design. Speed deviation $\Delta\omega_2$ is remote signal and $\Delta\omega_4$ is local signal to G_4. So, we form C matrix in normal and fault condition as below.

$$C_0 = \begin{bmatrix} c_2^T & c_4^T \end{bmatrix}^T = C, \quad C_2 = \begin{bmatrix} 0 & c_4^T \end{bmatrix}^T \tag{5.3}$$

where actual C matrix of plant G is $C = \begin{bmatrix} c_1^T & c_2^T & c_3^T & c_4^T \end{bmatrix}$, c_1, c_2, c_3 and c_4 corresponds to speed deviation output $\Delta\omega_1$, $\Delta\omega_2$, $\Delta\omega_3$ and $\Delta\omega_4$ respectively.

5.2.2 Conventional Control

The controller is represented as:

$$\dot{x}_c(t) = A_c x_c(t) + B_c y(t), \quad u(t) = C_c x_c(t), \quad K_c(s) \stackrel{s}{=} \left[\begin{array}{c|c} A_c & B_c \\ \hline C_c & 0 \end{array}\right] \tag{5.4}$$

The closed-loop state dynamics of this controller is defined as $\dot{\widetilde{x}} = \widetilde{A}\widetilde{x}$
where

$$\widetilde{A} = \begin{bmatrix} A_p & B_p C_c \\ B_c C_p & A_c \end{bmatrix} \tag{5.5}$$

5.2.2.1 Model Order Reduction

The plant model obtained after linearization is of 58^{th} order. This high order may lead to large computation time for synthesis of controller. So, the model order is reduced using Hankel reduction method and we get reduced order model of 8^{th} order shown in Fig.(5.19). The plant is of one input and two output system.

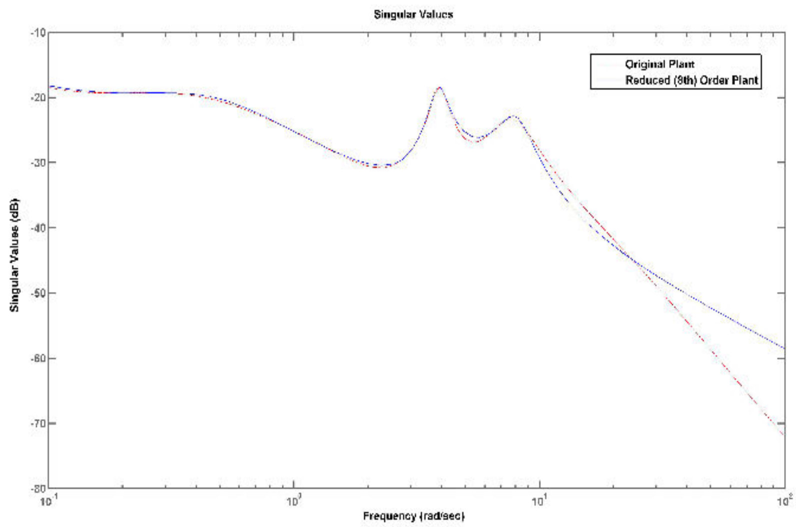

Figure 5.19: Singular value plot of full and reduced order plant

5.2.2.2 Controller Synthesis

Now through MATLAB, the three LMI defined for CC is run to find suitable controller K_c at normal condition which should work for both normal and fault conditions. The controller obtained is of 11^{th} order and is reduced to 8^{th} via Hankel method. The controller is of two input and one output model as shown in Fig.(5.20).

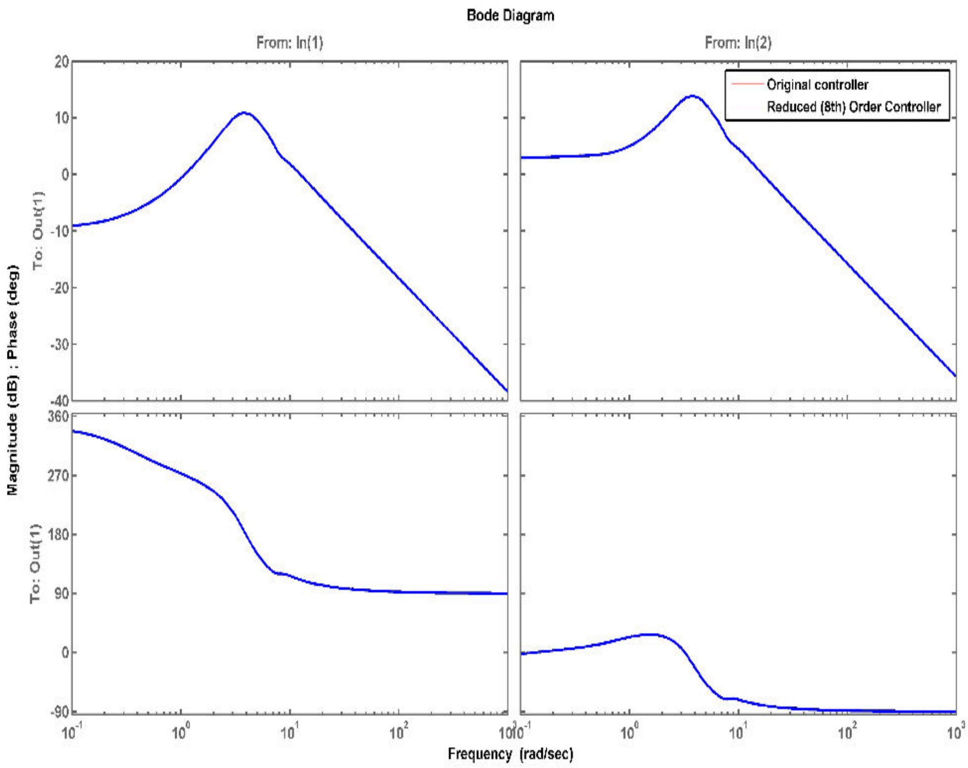

Figure 5.20: Bode plot of full order and reduced order conventional controller

Two cases are studied and observation are made on speed deviation $\Delta\omega_{24}$: 1) When plant is at normal condition 2) When plant loses remote signal $\Delta\omega_2$ after 10 seconds.

It can be seen through plot of Fig.(5.21) that in normal condition, CC controller is able to damp to good extent but in faulty condition it goes a bit unstable. So in order to damp oscillations to a good level without loss of stability, Passive FTC is designed further and studied.

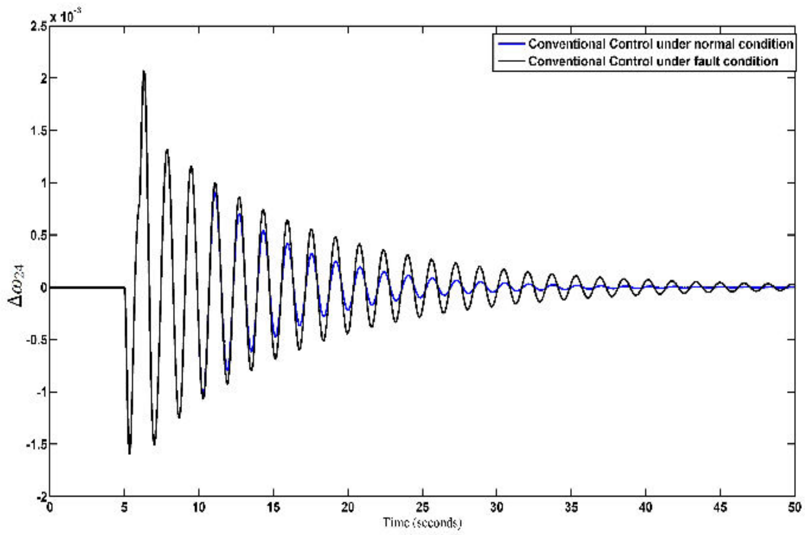

Figure 5.21: $\Delta\omega_{24}$ plot of CC in normal and fault condition

5.2.3 Passive FTC

Plant in passive FTC is same as that considered in CC with one input and two ouputs. The controller is represented as:

$$\dot{x}_f(t) = A_f x_f(t) + B_f y(t), \quad u(t) = C_f x_f(t), \quad K_f(s) \overset{s}{=} \left[\begin{array}{c|c} A_f & B_f \\ \hline C_f & 0 \end{array}\right] \tag{5.6}$$

The closed-loop state dynamics of this controller is defined as $\dot{\widetilde{x}} = \widetilde{A}\widetilde{x}$
where

$$\widetilde{A} = \begin{bmatrix} A_p & B_p C_f \\ B_f C_p & A_f \end{bmatrix} \tag{5.7}$$

5.2.3.1 Controller Synthesis

The iterative algorithm presented in section 4.3 is simulated in Matlab to obtain the controller K_f. The controller is of two input and input output model. Full order controller is of 11^{th} order and is reduced to 5^{th} order via Hankel reduction method.

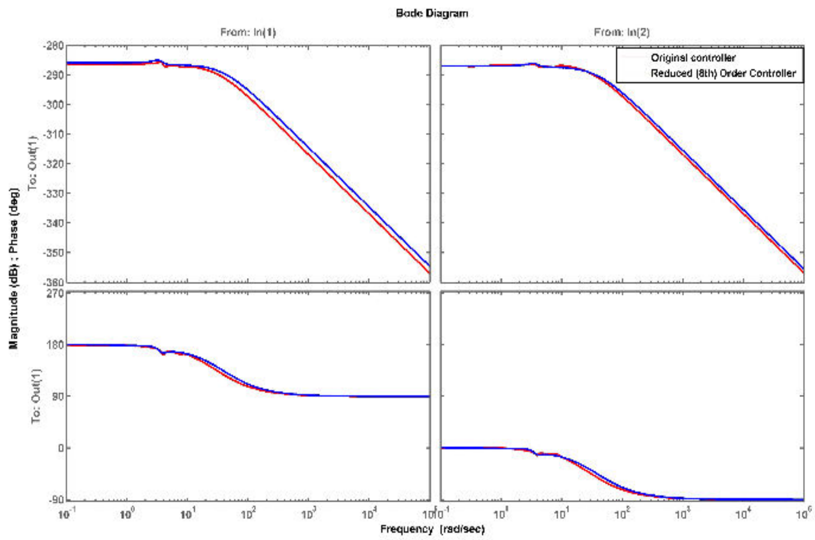

Figure 5.22: Bode plot of full order and reduced order fault tolerant controller

Two cases are studied and observation are made on speed deviation $\Delta\omega_{24}$: 1) When plant is at normal condition 2) When plant loses remote signal $\Delta\omega_2$ after 10 seconds.

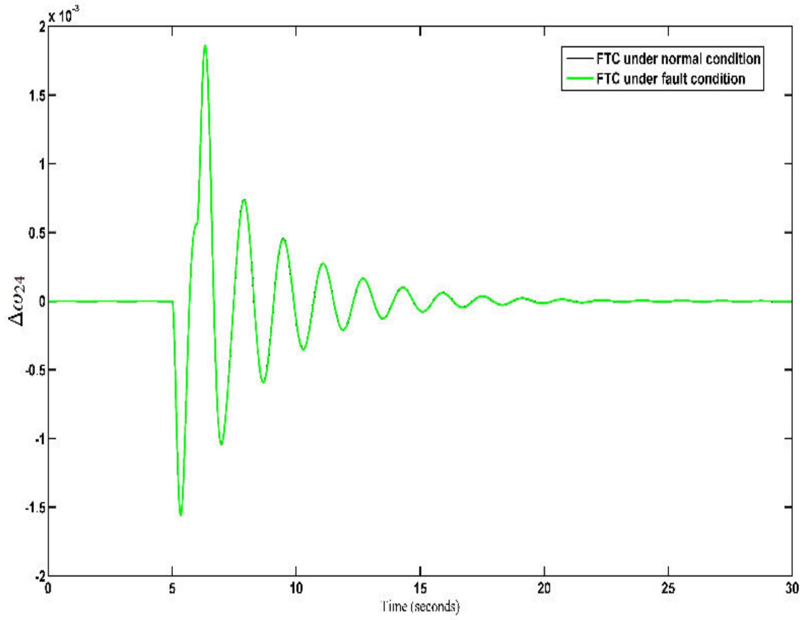

Figure 5.23: $\Delta\omega_{24}$ plot of FTC in normal and fault condition

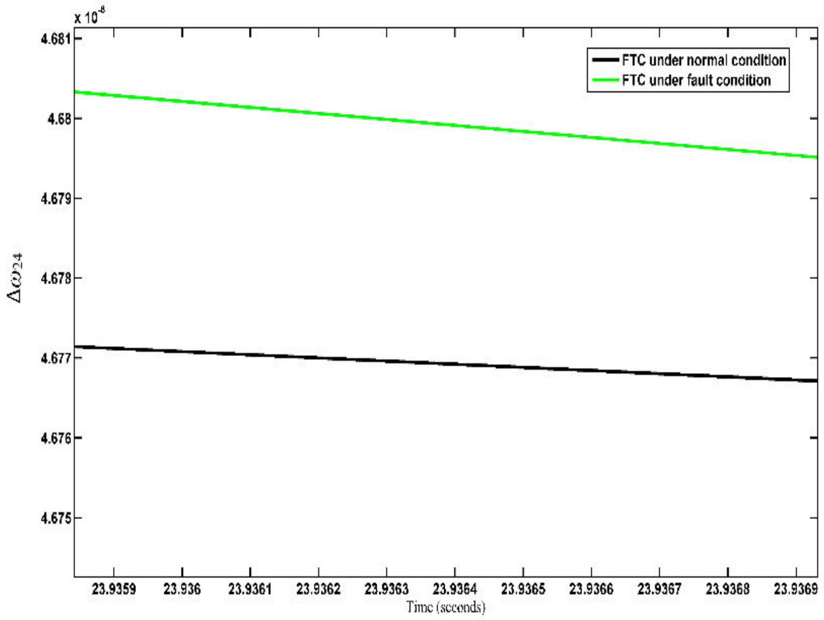

Figure 5.24: $\Delta\omega_{24}$ plot of FTC in normal and fault condition(plot zoomed)

Comparison of CC and FTC Results:

NORMAL CONDITION:

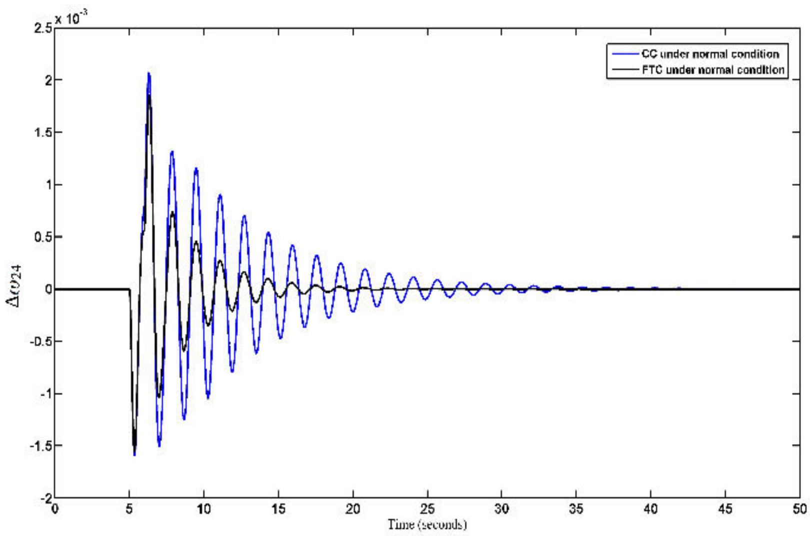

Figure 5.25: $\Delta\omega_{24}$ plot of CC and FTC in normal condition

FAULT CONDITION:

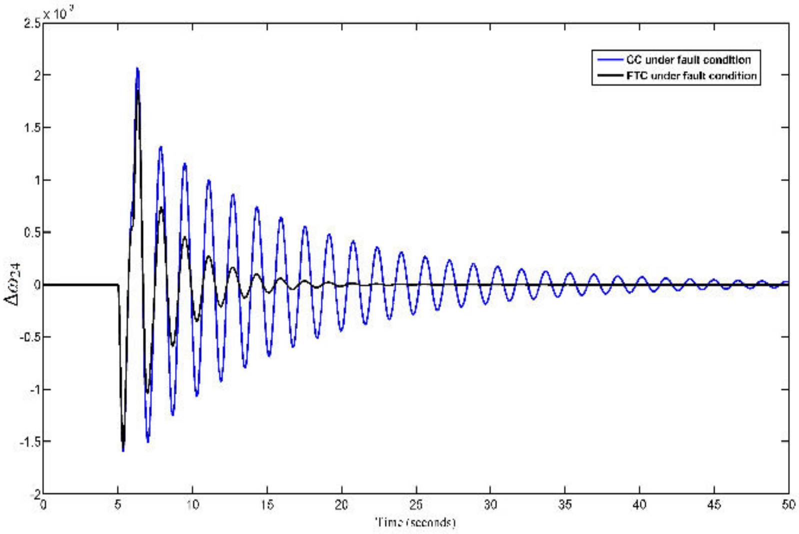

Figure 5.26: $\Delta\omega_{24}$ plot of CC and FTC in fault condition

Through plot of $\Delta\omega_{24}$ from Fig. (5.23), it is observed that FTC even in fault condition do not lose stability and maintains good damping ratio. From Fig. (5.12) and (5.23) observation can be made that the variation for normal and fault situation is very small for FTC compared to to CC plot. FTC_p requires more control effort compared to CC but former guarantees acceptable performance level even when a remote signal is lost. At last from Fig. (5.25) and (5.26), it is concluded that in both normal and faulty case, FTC damps inter-area oscillations quite before CC does i.e. it improves system performance to good extent.

CHAPTER 6

Conclusion and Future Scope

6.1 Conclusion

In this thesis, two case studies are taken. One to design wide-area controller to damp inter-area oscillations and the other to design fault tolerant controller to tackle the fault of remote signal and maintain stability of system. In first case, the system is modeled in MATLAB and modal analysis is performed and it is observed that local PSS could not damp inter-area mode as it has lack of observability of remote signal. As many remote signals are available thus many PMU units should be used and so the cost of it increase and it may effect other modes also. So in order to have efficient control, wide-area loop selection based on geometrical measures is done and loop corresponding to inter-area mode is selected. The mathematical model of plant is of large order which may increase the computation time to design controller. To solve this problem, model order is reduced by Hankel reduction method. With this reduced model, controller is designed. At first no-delay is considered and controller was efficient and robust a different operating conditions. However, when time-delay in the feedback loop is considered, it loses stability. The time-delay is modeled as 2^{nd} order Pade approximation as it gives good handle for delay. It is found that non-synchronous feedback configuration is more tolerable than synchronous configuration. It is shown that Non-Synchronous WDC works better than Synchronous-WDC.

The above case was for normal condition which an ideal condition but it may happen that a fault may occur in sensor and so a remote signal is lost. A Conventional Control study in normal and faulty condition is compared and found that when fault occurs then it loses stability. So, Passive Fault Tolerant Control was proposed to enhance the damping of inter-area oscillations. An iterative procedure is evolved to design an efficient controller to damp oscillations even in fault situation for FTC_p method. Under normal condition (when both local and remote signals are present), FTC requires more control effort compared to CC but it guarantees acceptable performance even if remote signal is lost whereas CC is not acceptable if fault occurs.

6.2 Future Scope

The present work of wide-area controller design results in good performance of system including effect of delays but further studies can be done. The controller can be designed with other methods such as networked control system and it may happen to achieve more better results with it. The present controller design is upon linear model but in real world the system is non-linear, so one can work on non-linear model to get exact results and better performance.

In case of fault of remote signals, the FTC design is based on passive iterative procedure. A further different approach can be done to give more better performance in fault condition. An Active FTC scheme is an approach where controller is not fixed and reconfigured whenever fault is detected and this approach can be studied further.

References

[1] *Robust Control in Power Systems.* Boston, MA: Springer US, 2005, ch. Mixed-Sensitivity Approach Using Linear Matrix Inequalities, pp. 115–138. [Online]. Available: http://dx.doi.org/10.1007/0-387-25950-3_8

[2] M. E. Aboul-Ela, A. Sallam, J. D. McCalley, and A. Fouad, "Damping controller design for power system oscillations using global signals," *Power Systems, IEEE Transactions on*, vol. 11, no. 2, pp. 767–773, 1996.

[3] A. Chakrabortty and P. P. Khargonekar, "Introduction to wide-area control of power systems," in *American Control Conference (ACC), 2013.* IEEE, 2013, pp. 6758–6770.

[4] N. R. Chaudhuri, A. Domahidi, R. Majumder, B. Chaudhuri, P. Korba, S. Ray, and K. Uhlen, "Wide-area power oscillation damping control in nordic equivalent system," *Generation, Transmission & Distribution, IET*, vol. 4, no. 10, pp. 1139–1150, 2010.

[5] H. Chen, H. Bai, M. Liu, and Z. Guo, "Wide-area robust h_∞ control with pole placement for damping inter-area oscillations," in *Power Systems Conference and Exposition, 2006. PSCE'06. 2006 IEEE PES.* IEEE, 2006, pp. 2101–2108.

[6] M. Chenine, K. Zhu, and L. Nordström, "Survey on priorities and communication requirements for pmu-based applications in the nordic region," in *PowerTech, 2009 IEEE Bucharest.* IEEE, 2009, pp. 1–8.

[7] M. Chilali and P. Gahinet, "h_∞ design with pole placement constraints: an lmi approach," *Automatic Control, IEEE Transactions on*, vol. 41, no. 3, pp. 358–367, 1996.

[8] A. Hamdan and A. Elabdalla, "Geometric measures of modal controllability and observability of power system models," *Electric power systems research*, vol. 15, no. 2, pp. 147–155, 1988.

[9] A. A. Hashmani and I. Erlich, "Delayed-input power system stabilizer using supplementary remote signals," *Control Engineering Practice*, vol. 19, no. 8, pp. 893–899, 2011.

[10] A. Heniche and I. Karnwa, "Control loops selection to damp inter-area oscillations of electrical networks," *Power Systems, IEEE Transactions on*, vol. 17, no. 2, pp. 378–384, 2002.

[11] M. Klein, G. Rogers, P. Kundur *et al.*, "A fundamental study of inter-area oscillations in power systems," *IEEE Transactions on Power Systems*, vol. 6, no. 3, pp. 914–921, 1991.

[12] P. V. Kokotovic, R. O'malley, and P. Sannuti, "Singular perturbations and order reduction in control theoryan overview," *Automatica*, vol. 12, no. 2, pp. 123–132, 1976.

[13] P. Kundur, N. J. Balu, and M. G. Lauby, *Power system stability and control.* McGraw-hill New York, 1994, vol. 7.

[14] R. Majumder, B. Chaudhuri, H. El-Zobaidi, B. Pal, and I. Jaimoukha, "Lmi approach to normalised h_∞ loop-shaping design of power system damping controllers," in *Generation, Transmission and Distribution, IEE Proceedings-*, vol. 152, no. 6. IET, 2005, pp. 952–960.

[15] F. Milano and M. Anghel, "Impact of time delays on power system stability," *Circuits and Systems I: Regular Papers, IEEE Transactions on*, vol. 59, no. 4, pp. 889–900, 2012.

[16] B. Naduvathuparambil, M. Valenti, A. Feliachi *et al.*, "Communication delays in wide-area measurement systems," in *Southeastern Symposium on System Theory*, vol. 34. Citeseer, 2002, pp. 118–122.

[17] A. Patel, "A study on wide-area controller design and effect of delays in power systems," Ph.D. dissertation, National Institute of Technology, Rourkela, 2015.

[18] A. Phadke and R. M. de Moraes, "The wide world of wide-area measurement," *Power and Energy Magazine, IEEE*, vol. 6, no. 5, pp. 52–65, 2008.

[19] R. A. Ramos, L. F. Alberto, and N. G. Bretas, "A new methodology for the coordinated design of robust decentralized power system damping controllers," *Power Systems, IEEE Transactions on*, vol. 19, no. 1, pp. 444–454, 2004.

[20] C. Scherer, P. Gahinet, and M. Chilali, "Multiobjective output-feedback control via lmi optimization," *Automatic Control, IEEE Transactions on*, vol. 42, no. 7, pp. 896–911, 1997.

[21] F. R. Segundo Sevilla, "Fault-tolerant wide-area control of power systems," 2013.

[22] F. R. Segundo Sevilla, I. Jaimoukha, B. Chaudhuri, and P. Korba, "Fault-tolerant control design to enhance damping of inter-area oscillations in power grids," *International Journal of Robust and Nonlinear Control*, vol. 24, no. 8-9, pp. 1304–1316, 2014.

[23] F. R. Segundo Sevilla, I. M. Jaimoukha, B. Chaudhuri, and P. Korba, "A semidefinite relaxation procedure for fault-tolerant observer design," *Automatic Control, IEEE Transactions on*, vol. 60, no. 12, pp. 3332–3337, 2015.

[24] S. Skogestad and I. Postlethwaite, *Multivariable feedback control: analysis and design.* Wiley New York, 2007, vol. 2.

[25] X. Xie, J. Xiao, C. Lu, and Y. Han, "Wide-area stability control for damping inter area oscillations of interconnected power systems," *IEE Proceedings-Generation, Transmission and Distribution*, vol. 153, no. 5, pp. 507–514, 2006.

[26] Y. Zhang and A. Bose, "Design of wide-area damping controllers for interarea oscillations," *Power Systems, IEEE Transactions on*, vol. 23, no. 3, pp. 1136–1143, 2008.